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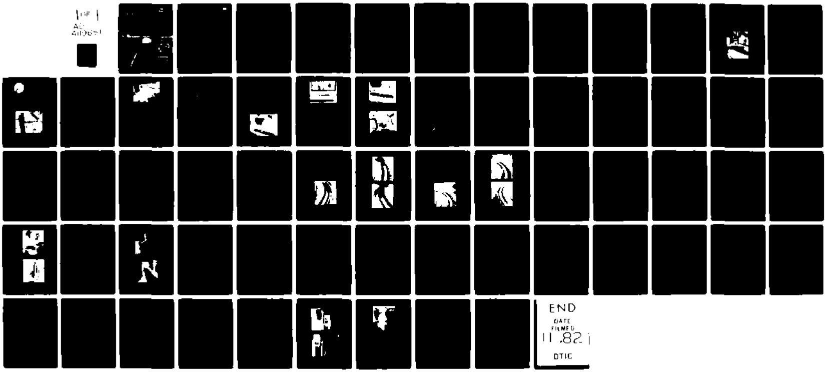

# CRREL
# REPORT 82-18

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

## *Optimizing deicing chemical application rates*

CRREL Report 82-18

August 1982

# Optimizing deicing chemical application rates

L. David Minsk

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FEDERAL HIGHWAY ADMINISTRATION
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Snow and ice control on highways has come to rely heavily on the use of sodium chloride to maintain a trafficable surface for unimpeded movement. Empirical approaches have led to a wide range of application rates, some clearly excessive, but justified on the ground of safety and expediency. The combination of environmental degradation from the huge quantities of salt entering the environment, along with the increased cost of salt itself and the cost of its application have spurred the search for more precise knowledge of the proper amount of salt to apply to a pavement, considering a range of environmental, traffic and chemical parameters. Since controlled tests in the field are extremely difficult to make, a circular test track of three test pavements, dense-graded asphaltic concrete (DGA), open-graded asphaltic concrete (DGA) and portland cement concrete (PCC), was constructed in a coldroom. Natural snow and ice

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were applied to the pavements and an instrumented slipping wheel was driven over the surfaces to generate frictional forces. These forces were measured and then used to evaluate the response to salt application with time for three test temperatures. OGA had the lowest friction values at a temperature near the freezing point, but higher initial values or more rapidly increasing values than DGA and PCC following salt application at the two lower temperatures. Optimum application rate of salt on PCC and DGA lies between 100 and 300 lb/lane mile (LM), and a higher rate resulted in slight or no improvement in friction. DGA showed anomalous results: lower friction for 300 lb/LM and higher friction for both 100 and 500 lb/LM.

## PREFACE

This report was prepared by L. David Minsk, Research Physical Scientist, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by the Federal Highway Administration, Offices of Research and Development.

The manuscript of this report was technically reviewed by Dr. William Harrison and Dr. Ronald Liston of CRREL.

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## CONTENTS



## ILLUSTRATIONS

Figures

## TABLES

## CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E380).

| *Multiply* | *By* | *To obtain* |
|---|---|---|
| inch | 25.4* | millimeter |
| foot | 0.3048* | meter |
| $inch^2$ | 645.16* | $millimeter^2$ |
| foot/second | 0.3048* | meter/second |
| mile/hour (mph) | 1.609344* | kilometer/hour |
| pound | 0.4535924 | kilogram |
| ton | 907.1847 | kilogram |
| pound-force | 4.448222 | newton |
| pound-force/$inch^2$ (psi) | 6.894757 | kilopascal |
| pound-force-inch | 0.1129848 | newton-meter |
| degrees Fahrenheit | $t_{°C}=(t_{°F}-32)/1.8$ | degrees Celsius |

* Exact

# OPTIMIZING DEICING CHEMICAL APPLICATION RATES

L. David Minsk

## INTRODUCTION

In attempting to attain a trafficable surface, highway maintenance personnel generally use empirical information for estimating the quantity of deicing chemical to apply to melt snow or ice on pavements. When there is doubt regarding the minimum quantity required for a given condition, an amount greatly in excess of that actually required may be applied. Excessive quantities of deicing chemicals have often had deleterious effects on the roadside environment, on surface and groundwater supplies, and on structures such as bridge decks. Though the supply of common deicing chemicals is inexhaustible, their cost continues to rise, making reduction in the quantity applied an economic as well as an environmental imperative. Use of deicing chemicals can be reduced by establishing a relatively narrow range of quantities required to achieve, within a specified time, a given effect when influenced by a prescribed set of climatic and other external factors. Of course, automobile corrosion is also accelerated by the application of common deicing chemicals. However, reduced use of these chemicals would probably have little effect on the corrosion problem, since the minimum concentration necessary to initiate electrochemical action would still be present.

## OBJECTIVES

The objectives of this research were to determine optimal concentrations of chloride deicing salts required to achieve desired service levels under a wide range of traffic and environmental conditions, and prepare guidelines to assist the winter maintenance engineer or supervisor in selecting the appropriate chemical treatment for current conditions.

## BACKGROUND

Movement of tracked or wheeled vehicles across a snow- or ice-covered surface requires an adequate coefficient of friction between the driving element and the surface. Just what is "adequate" will depend on many external circumstances such as the speed and size of the vehicle, roadway grade, vehicle speed changes, and the direction of movement. The coefficient of friction between rubber tires and snow or ice can be increased by two practical methods: 1) by distributing a covering of water-insoluble particulates over the snow or ice, or 2) by destroying the surface homogeneity of the snow or ice by chemical means, eventually exposing the pavement. The first method does not require complete coverage of the surface for significant traction improvement, and a discontinuous scattering of sand, cinders, slag, or gravel, all termed "abrasives," can suffice temporarily. However, the method favored in most heavily populated areas of the world where temperatures are not extremely low is the application of a water-soluble chemical, generally sodium chloride, calcium chloride, magnesium chloride or mixtures of these, to melt the surface and ultimately to break the bond between the compacted snow or ice mass and the pavement so that mechanical means can be used to remove the residue. Oftentimes traffic action is sufficient to accomplish this objective

without the intervention of plows. New snow can be prevented from being compacted by traffic into a layer tightly bonded to the pavement by addition of a chemical deicing agent. This keeps the mass "mealy" and incapable of forming a bond. The popularity of chemical means of snow and ice control is reflected in the quantity of sodium chloride applied across the United States: approximately 9,000,000 tons annually.

## APPROACH

The objective measure chosen for the change in the characteristics of snow- or ice-covered pavement surfaces with time following the application of a deicing chemical is the coefficient of friction between rubber and the surface. (It is more proper to refer to the resistive force as "interface shearing resistance" and its ratio to the normal force as the "angle of interface shearing resistance" rather than coefficient of friction; this is discussed in a later section.) Once the coefficient of friction required for vehicular operation under specified conditions has been established and a maintenance level chosen, it should be theoretically possible to select the quantity of chemical required to achieve a desired surface condition. As an illustration, assume that a hill site is to be treated; assume also that tests have shown that the pavement surface and gradient require a tire-pavement coefficient of friction of 0.40 for the permitted speeds and desired stopping distance. The maintenance level for the site dictates that this coefficient of friction must be achieved within 15 min after treatment. These factors, together with a set of environmental factors to be discussed later, will be sufficient to make an informed choice of the amount of chemical to apply if the chemical reaction rates are known. It is these reaction rates, represented by the change in the coefficient of friction with time, which have not been known precisely enough for practical application. The research reported here seeks to determine them.

Two types of laboratory tests were performed: point tests on untrafficked snow- and ice-covered test sections, and rolling tire tests on a circular track. Two devices were developed for measuring change of surface friction with time: a rotating rubber annulus for making the point measurements, and a slipping wheel for measuring the effects of trafficking the pavement. The British Portable Tester (ASTM 1974) was also used on snow but proved unsuitable. The rotating annulus, termed the surface friction gauge (SFG), was also used for making measurements in the field. Contracts were awarded to the Rochester Institute of Technology (RIT) and Pennsylvania State University (Penn State) to perform field observations on artificially trafficked roads to extend the laboratory findings. Late delivery of the surface friction gages intended for use by these investigators limited the comparison of field with laboratory data; the results of those field projects are contained in Appendices B and C.

## INFLUENCING FACTORS

### Field factors

Some of the relevant factors influencing chemical control of a snow- or ice-covered pavement include

1. Air and pavement temperature and temperature change.
2. Nature of chemical (solubility, heat of solution).
3. Chemical treatment level.
4. Timing and frequency of treatment.
5. Form of chemical application (i.e. liquid or solid.
6. Number of wheel passes and speed.
7. Type of precipitation.
8. Depth of precipitation.
9. Pavement type.
10. Radiant energy intensity.
11. Humidity.
12. Wind speed.

During the early stages of the study the large circular track was not yet constructed. In order to give initial data on several parameters, the point measurements (using the SFG) were made with the knowledge that these omitted the important parameter of traffic.

### Laboratory

All but the last three factors listed above were incorporated in the experimental design (however, usable data were obtained only for solid sodium chloride). Additional factors related to the measurement of the angle of interface shearing resistance include

1. Type of rubber.
2. Normal load on friction device.
3. Differential interface velocity (relative motion between the slipping surfaces).

The laboratory experiments incorporated the following conditions:

1. Pavement types (see Appendix A)
   a. Portland cement concrete (PCC).
   b. Open-graded asphaltic concrete (OGA).
   c. Dense-graded asphaltic concrete (DGA).
2. Surface friction gage rubber
   a. ASTM E501 (ASTM 1976).
   b. Proprietary formulations.

3. Air temperatures
   a. 10°F (-12°C).
   b. 20°F (-6.7°C).
   c. 30°F (-1.1°C).

## LABORATORY TRAFFICKING TESTS

Continuous trafficking of the circular track pavements was accomplished using a Michelin ZX radial tire, size 145SR10. This was the largest size of commercial tire that could be mounted on the test apparatus. The selection was made with the full realization that a snow tire rather than a smooth ASTM E524 (ASTM 1976a) tire of known rubber composition would invalidate exact comparison with other investigators' skid tests. An electric garden tractor (Wheel Horse Elec-Trak Model C-185) was modified by removing the front end and attaching a support frame for the test tire (Fig. 1). The test tire was driven at a constant speed relative to the rear drive wheels by a chain drive and gear reducer linkage (Fig. 2). A range of positive and negative slip ratios was available by interchanging gears $G_T$ and $G_J$. Slip mode rather than locked-wheel braking was chosen to measure frictional resistance for two reasons: 1) maximum frictional resistance is developed not with a locked wheel but with some slip (Schallamach 1971, Shah and Henry 1977), and 2) the snow surface would be less disturbed so that the test would be a more realistic evaluation of the primary effect of deicing chemical action over the 60-min test period. Friction between rubber and hard snow reaches a maximum at about 30% slip in the case of an accelerating (driving) snow tire, and at about 25% for a decelerating (braking) snow tire at 6 mph. The maximum coefficient of friction in braking on clear but wet asphalt occurs at slightly lower slips, around 15-20% (Schallamach 1971).

Slip $i$ is defined as the ratio of the decreased (or increased) speed to the initial speed, or alternatively,

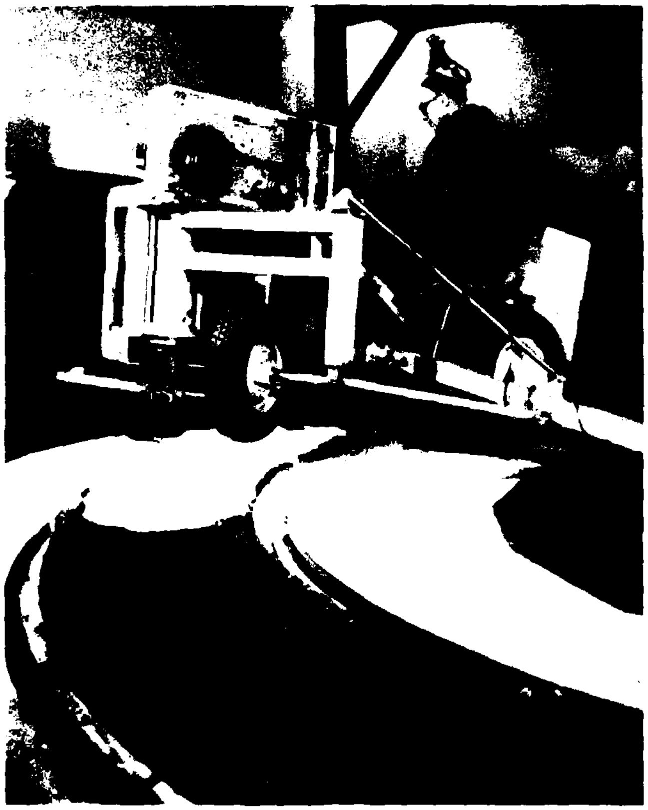


*Figure 1. Modified electric garden tractor supporting a test tire (Michelin 145SR10) in an instrumented load frame and tethered to rotate around a test track.*

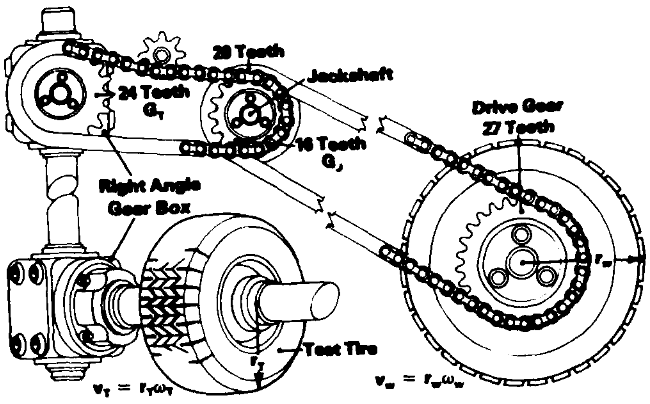



*Figure 2. Schematic of drive linkage between tractor drive wheel (on right) and test tire to generate a selectable, constant slip rate between the test tire and pavement.*

the ratio of the difference between theoretical and actual speeds to the theoretical speed. Pure circumferential slip is

$$i = \frac{v_t - v_a}{v_t} = \frac{v_i}{v_t} = 1 - \frac{v_a}{v_t} \qquad (1)$$

where $v_t$ = the vehicle speed represented by a freely rolling wheel (sometimes called the "theoretical" speed)

$v_a$ = the actual speed of the vehicle or of the slipping wheel

$v_i$ = differential interface velocity (DIV).

In braking, $v_t > v_a$ and $i$ is positive with a maximum of 1 for a locked wheel. In accelerating, $v_t < v_a$ and $i$ is negative, becoming $-\infty$ when a stationary wheel spins (Schallamach 1971).

Several drawbacks result from the use of $i$ as a measure of relative velocity between the test tire and pavement. There is a discontinuity in $i$ when $v_t = 0$ because $i$ approaches $-\infty$ as $v_t$ approaches zero from the positive side, and $i$ approaches $+\infty$ as $v_t$ approaches zero from the negative side. A more serious disadvantage is that slip does not represent a unique relationship between theoretical and actual velocities. It is dependent on test speed: 20% slip at 5 mph has a different differential interface velocity than 20% slip at 10 mph. The use of DIV ($= iv_t$) avoids this imprecision.

## FORCE MEASUREMENT AND COEFFICIENT OF FRICTION

The coefficient of friction $\mu$ is a measure of the resistance to sliding due to gravitational forces. On a material such as snow or ice, the cohesion of the surface material plays a role in the frictional resistance. Shearing of the compacted snow lying between the sliding rubber and the solid pavement can occur and in effect imparts a viscous drag on the sliding surface.

The resistive force $F_w$ due to gravitational effects is the classical expression

$$F_w = \mu N \qquad (2)$$

where $\mu$ the coefficient of friction and $N$ the normal force.

The resistive force $F_c$ due to cohesion is

$$F_c = AC \qquad (3)$$

where $A$ is the contact area between sliding surfaces and $C$ the cohesion of the surface material (i.e. shear stress to break the bonds).

If the effects due to tire rubber deformation and tearing are neglected, the total resistive force $F_T$ is then the following sum:

$$F_T = F_w + F_c = \mu N + AC = \mu_i N \qquad (4)$$

where $\mu_i$ is defined as the interfacial shearing angle (Fig. 3) and

$$\mu_i = \tan^{-1} \frac{F_T}{N} = \tan^{-1} \left(\frac{\mu N + AC}{N}\right)$$

$$= \tan^{-1} \left(\mu + \frac{AC}{N}\right). \qquad (5)$$

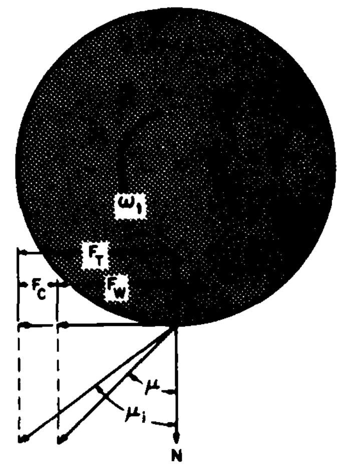



*Figure 3. Equality of coefficient of friction $\mu$ and ratio $F_w/N$.*

Friction between a slipping tire and snow (and to a lesser extent ice) is thus seen to be the sum of two components, one of which depends on contact area. Since it is difficult, and in fact unnecessary, to separate these terms for the purpose of the tests performed in this study, $\mu_i$ will be used and referred to as the angle of interface shearing resistance in preference to coefficient of friction.

The force developed at the interface of the slipping tire and the pavement is transmitted through the axle to the hinged load frame. This force is resisted by a mechanical link between the movable arm and the tractor; a strain gauge (Interface SM-500) is inserted in the mechanical link to measure this resistive force (Fig. 4). A compressive (or tensile) force can be generated depending on whether positive (or negative) slip is present; e.g. when the test tire is braked it turns more slowly than a free rolling tire ($v_t > v_a$) and therefore forces the movable arm against the resisting link, producing a compressive force. The output of the strain gauge is read on a strip chart recorder mounted on the tractor.

The configuration of the movable arm of the load frame is shown schematically in Figure 5. The distance $x$ from the load frame hinge was measured to the center of the test tire (in practice, the wheel rim was used as the reference and the tire center to rim distance, 3.12 in., was added). A simple force balance gives

$$F_w = \left(\frac{23.9}{x}\right) \qquad (6)$$

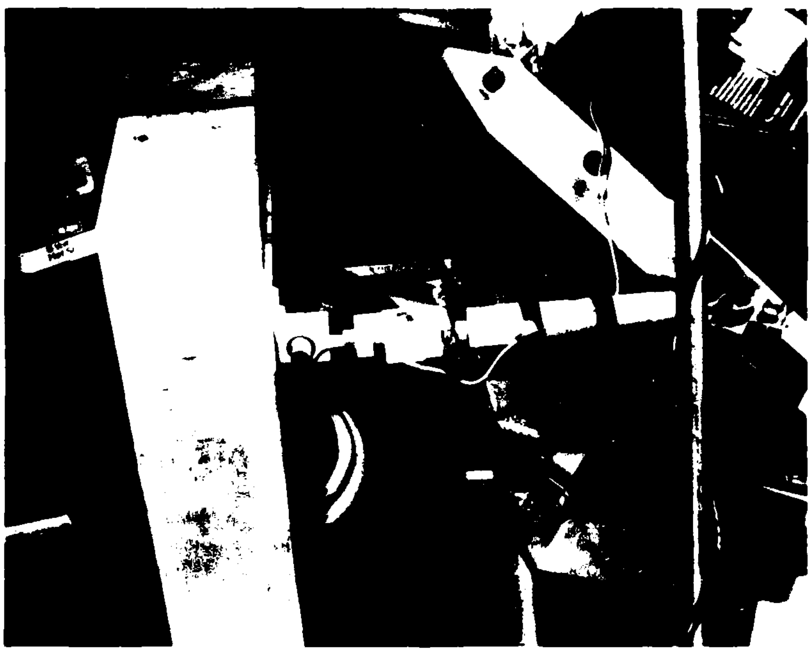


*Figure 4. Load cell inserted in link between the test tire load frame and the tractor to measure tire/pavement frictional force.*

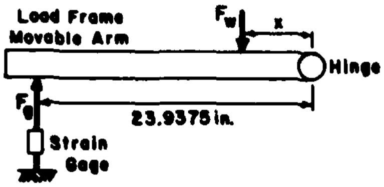



*Figure 5. Geometry of the load frame.*

where $F_w$ is the frictional force in the plane of tire rotation generated by the tire slipping on the pavement, and $F_g$ is the reaction force on the strain gauge.

$F_g$ was obtained from the strip chart record and calibrated using a 250-lbf calibration load. The load on the tire was determined directly by using a load cell measuring the force to lift the load frame. The point of attachment was the top of the frame directly above the test tire. The operator sat on the tractor, as he did during test periods, for this weighing, and the same operator was used in all tests. The tire load depended on wheel position, varying from 350 lbf at a distance of 10 1/2 in. from the hinge to 400 lbf at 19 3/4 in. from the hinge. A simple calculator program was written to facilitate calculation of the interface shearing resistance using measured values of test conditions and the strip chart record.

## TEST TIRE SLIP

The test tire was mounted on the movable arm of the load frame attached to the front of the electric tractor and was driven through a mechanical linkage by the right rear tractor wheel (Fig. 2 and 6). The two rear tractor wheels straddled the test track, but only the right wheel was driven, though the left wheel could be engaged if desired. A radius arm or tether constrained the tractor to describe a circle of radius $R_w$ to the center of the drive wheel (Fig. 7). The test tire could be moved laterally over a distance of 18 in. by means of an electric linear actuator but it too was constrained to a circle of radius $R_T$.

Since the drive wheel is assumed to have zero slip (a reasonable assumption, because of the weight of the tractor and the relatively large radius, confirmed by tracking the contact area on paper), the angular velocity of the wheel is equal to the velocity of the center of mass $V_{w(cm)}$ divided by the radius of the tire $r_w$, or

$$\omega_w = \frac{V_{w(cm)}}{r_w} = \frac{V_w}{r_w} \quad (V_w \cong V_{w(cm)}) \qquad (7)$$

where $V_w$ = tangential velocity of the wheel around track. Similarly, the angular velocity of the free rolling test tire $\omega_T$ is

$$\omega_T = \frac{V_T}{r_T} \qquad (8)$$

where $V_T$ = tangential velocity of the test tire around track

$r_T$ = radius of test tire.

The ratio of these angular velocities yields

$$\omega_T = \omega_w \left(\frac{R_T}{R_w}\right)\left(\frac{r_w}{r_T}\right), \text{ since } \frac{V_T}{R_T} = \frac{V_w}{R_w}. \qquad (9)$$

A 27-tooth drive gear on the drive wheel was connected by a chain to a 20-tooth gear on a jackshaft mounted on top of the fixed load frame. A second chain linked gears $G_J$ on the jackshaft and $G_T$ on the right-angle 1:1 gearbox (Browning 9HB1-LR10) on the load frame top. An identical gearbox drove the test wheel axle. An electric clutch on the jackshaft enabled the operator to switch to either a free rolling or slip condition. Tests were conducted to ensure that the clutch was truly locked so that the clutch would not slip when energized.

The angular velocity $\omega_T'$ of the test tire as driven by the tractor drive wheel is

$$\omega_T' = \omega_w \left(\frac{27}{20}\right)\left(\frac{G_J}{G_T}\right) = 1.35\, \omega_w \frac{G_J}{G_T} \qquad (10)$$

where $G_J$ is the number of teeth on interchangeable jackshaft gear and $G_T$ the number of teeth on interchangeable right-angle drive gear.

Using the definition of slip (eq 1), but substituting the respective angular velocities (valid since $\omega \propto v$),

$$i = \frac{\omega_T - \omega_T'}{\omega_T} = 1 - \frac{\omega_T'}{\omega_T}$$

$$= 1 - 1.35\left(\frac{r_t}{r_w}\right)\left(\frac{R_w}{R_T}\right)\left(\frac{G_J}{G_T}\right). \qquad (11)$$

As described earlier, a more important parameter derived from this relationship is differential interface velocity $V_i$, i.e. the difference in velocities $V_T - V_T'$ between pavement or snow/ice and the tire surface, or the contact patch sliding speed:

$$V_i = V_T - V_T' = r_T\,(\omega_T - \omega_T')$$

$$= V_w \left\{\frac{R_T}{R_w} - 1.35\left[\left(\frac{r_T}{r_w}\right)\left(\frac{G_J}{G_T}\right)\right]\right\}. \qquad (12)$$

*Figure 6. Test tire showing axle along which it could be moved laterally by means of an electric linear actuator.*

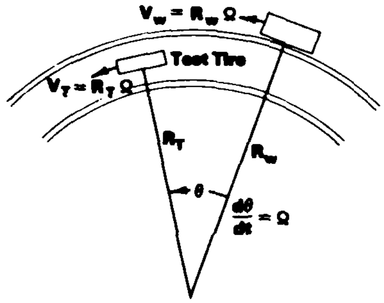



*Figure 7. Plan view schematic of the tractor on the test track showing the kinematic relationships.*

(Note: only the rotational velocities of the free rolling and slipping wheels need to be considered since the translational velocities are the same and thus are eliminated by subtraction.)

As a typical experimental condition used in many of the tests reported here, the following values were measured:

$R_T$ = 74.25 in. (to center of test tire)
$R_w$ = 89.7 in. (to center of drive tire)
$r_T$ = 8.78 in. (with normal operating load, tire pressure 20 psi)
$r_w$ = 10.5 in. (with normal operating load, tire pressure 12 psi)
$G_I$ = 16
$G_T$ = 24
$V_w$ = 4.7 ft/s (3.2 mph)

$$i = 1 - \frac{(1.35)(8.78)(89.7)(16)}{(10.5)(74.25)(24)} = 0.091 = 9.1\% \tag{13}$$

$$V_i = (4.7)(12)\left[\frac{74.25}{89.7} - \frac{(1.35)(8.78)(16)}{(10.5)(24)}\right]$$

$$= 4.24 \text{ in./s.} \tag{14}$$

## SURFACE FRICTION GAUGE

For the static tests to determine surface friction, a surface friction gauge was developed. The design of this instrument is based on that of the bevameter used for measuring snow properties (Society of Automotive Engineers 1967). The principle is simple: measure the resistance that the test surface offers to the rotation of a rubber-covered annulus forced in contact with the surface by a known weight. Many practical problems make this procedure more complex, however. The original concept called for

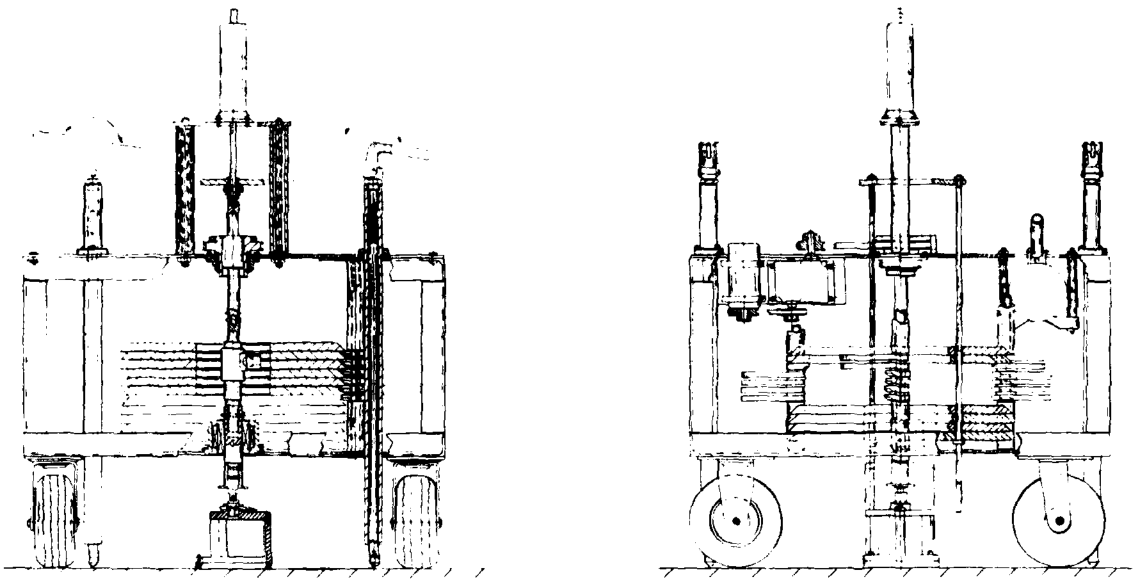


*Figure 8. Surface friction gauge.*

a completely self-contained device operating by battery power, but speed variation of low voltage, high current motors under load is so great that this approach had to be abandoned in favor of 110-V components. This posed no problem in the laboratory but it did restrict ease of use in the field since either line power or a generator must be used.

The arrangement of the SFG can be seen in Figure 8. The frame, made of 2- x 2-in. aluminum angle, measures 3x 3x 1.5 ft high. Six weights, each 50 ± 0.1 lb, slide on guides forming a load basket; the chosen number of weights can be placed on the load basket and the unused ones supported by paddles that can be flipped in and out. A hydraulic cylinder actuated by a hand pump is used to lift the rotating shaft and the weights. A needle valve controls the flow to drop the annulus onto the test surface at a constant speed. The area of the test surface of the rotating annulus measured 10 in.$^2$ for the initial laboratory tests. However, field tests demonstrated that the outer diameter of 6.53 in. extended beyond the walls of a wheel track and made it difficult to obtain repeatable friction measurements. A smaller annulus was designed having an outer diameter of 3.92 in. and area of 5 in.$^2$. This assisted greatly in obtaining data from wheel tracks.

The frictional force between the sliding rubber and pavement or snow/ice, required for calculation of the angle of interface shearing resistance $\mu_i$, was measured in terms of torque. A 500-lbf-in. torque cell (A.L. Design Inc.) was mounted in the drive shaft. $\mu_i$ was calculated from

$$\mu_i = \frac{F_T}{N} = \frac{T}{r_e N} \tag{15}$$

where $T$ is the torque (lbf-in.) and $r_e$ the effective radius of annulus (in.).

The effective radius satisfies the relation $T = r_e F$ and is calculated from

$$r_e = \frac{2}{3}\left(\frac{r_o^3 - r_i^3}{r_o^2 - r_i^2}\right) \tag{16}$$

where $r_o$ is the outside radius of annulus and $r_i$ the inside radius of annulus.

The annulus shaft was driven by a 1/4-hp variable speed motor through a reducing gear. Chain drive was used between this and the annulus shaft. A needle bearing sliding on a splined shaft allowed the annulus shaft to be moved up or down while rotating. Two of the rubber-tired wheels on the frame were rigid, and two swiveled but could be locked in place. However, the tires were not suitable for transferring the reaction torque to the test surface. Instead, three jack rods were provided to elevate the entire apparatus. The lower tips were pointed to penetrate snow or ice, and also worked well on bare pavement. Coarse adjustment of the jack height was possible with a threaded collar; bubble levels were used for adjusting the jacks

so that they would be parallel to the pavement or test surface. Toggle levers provided a rapid means of elevating the frame about 2 in. off the ground.

The rubber test surface was attached to a 4-in.-high cage. The annulus shaft has a 4-in. stroke for operation in snow of that depth. However, in all the tests the snow was either compacted or no deeper than 2 in. uncompacted. The annulus shaft weighed 20 lb with the 10-in.$^2$ annulus (19 lb with the 5-in.$^2$ annulus). This weight was added to the number of load plates used for the total normal force on the test surface. Trials with the 10-in.$^2$ annulus used all six weights so that the vertical force was 320 lbf; three weights were used with the 5-in.$^2$ annulus, giving a vertical force of 169 lbf.

Prior to use, all rubber test surfaces were abraded with five rotations of the annulus under the above loads on 60-grit silicon carbide abrasive paper. A rotation speed of 6 rpm was used for the 10-in.$^2$ annulus, resulting in a differential interface velocity $V_i$ of 1.89 in./s. So that approximately the same interface velocity would be maintained with the 5-in.$^2$ annulus, it was rotated at 9 rpm ($V_i$ = 1.64 in./s). Table 1 summarizes these dimensions. Microswitches were used to stop the rotation in both the forward and reverse directions. A mechanical stop prevented rotation past 345°. Continuous rotation was avoided because a direct cable connection rather than a slip ring was used for the torque cell.

**Table 1. Characteristics of the surface friction gauge test surfaces.**

| Dimension | Annulus area (in.$^2$) 10 | 5 |
|---|---|---|
| $r_o$, outside radius (in.) | 3.26 | 1.96 |
| $r_i$, inside radius (in.) | 2.74 | 1.50 |
| $r_e$, effective radius (in.) | 3.01 | 1.74 |
| $V_i$, differential interface velocity (in./s) | 1.89 | 1.64 |

## TEST PROCEDURE

*Static tests.* Natural snow harvested following snowfalls and stored in plastic bags in a coldroom at 10°F was sieved onto the 2-x 5-ft x 2-in.-thick pavement sections through a U.S. Standard Sieve no. 8 (2.38-mm openings) to provide a uniform and reproducible surface (Fig. 9). Compaction was achieved by standing on a board covering the snow for the tests in which the entire snow surface was compacted, and for the

*Figure 9. Method of sieving cold natural snow onto test pavements to obtain a uniform, reproducible surface.*

*Figure 10. Annulus of surface friction gauge entering snow cover while rotating.*

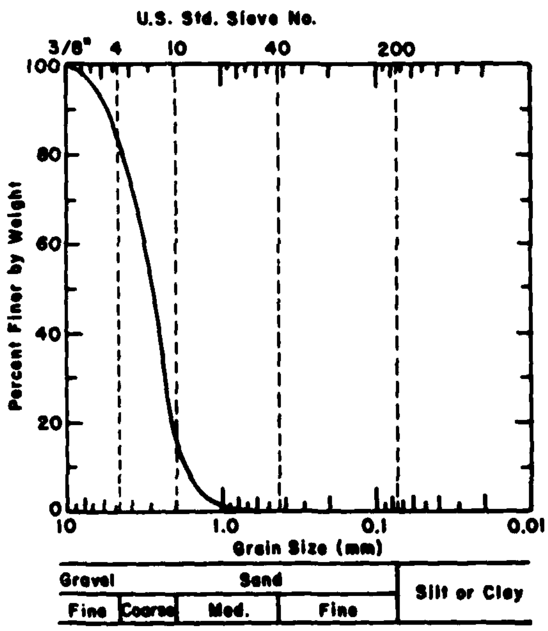



*Figure 11. Gradation of salt (NaCl) used in static and trafficked tests.*

other tests, the weight of the surface friction gauge was used to compact only the snow under the rotating annulus. Early trials showed that the best results were obtained by starting the rotation of the annulus prior to contacting the snow, thus eliminating the more variable and higher static friction (Fig. 10).

Salt (sodium chloride) having the gradation shown in Figure 11 was applied by shaking a pre-weighed quantity from a small aluminum foil dish (Fig. 12). This method proved to be far more uniform and reproducible than that employing mechanical shakers and spreaders. The quantity was based on a highway application rate of 100 to 500 lb/lane mile (LM). It required either the measurement of an arbitrary snow area or the preparation of a constant area in order that salt could be weighed at a convenient time before starting an experiment; the latter method was generally used. Several friction measurements were run on the untreated snow, the salt was then applied uniformly over the snow accumulation, and friction measurements were made over time using a new area for each. In some tests samples of snow were collected during the test period in order to determine the change of chloride ion concentration with time (Fig. 13).

*Figure 12. Applying pre-weighed amount of salt to a measured area of snow to obtain a uniform, reproducible distribution at a known application rate.*

*Figure 13. Sampling snow on which salt has been applied in order to make chloride ion concentration analysis.*

*Rolling tire (circular track) tests.* Snow was applied on the test track pavements by sieving as in the static tests. However, compaction was accomplished by the rolling wheel. Though the original intention was to traverse most of the 18-in.-wide pavement during a single test, the actual procedure restricted the rotation to a fixed tire path because

1. A limited amount of snow was available, particularly during the non-winter test periods, and therefore only the tire width plus a small excess was actually covered with snow.
2. A greater number of wheel passes could be made during the same melting period by limiting rotation to a single wheel path.
3. The fixed position meant that the slip rate was constant during a test.

Following six circular track rotations with the free-rolling tire, three passes were made while recording wheel reaction force with the electric clutch engaged and the wheel slipping. Salt was then applied by shaking the preweighed amount based on the desired application rate and the snow area, much like the static tests. Trafficking was immediately resumed, the operator engaging the clutch and recording wheel slip force periodically, usually every 10 min. A revolution counter tallied the number of tractor rotations.

## BRITISH PORTABLE TESTER

The British Portable Tester, a pendulum device, was investigated for applicability to measuring frictional force on a snow surface. The procedure described in ASTM E303-74 (ASTM 1974) was used. A number of tests confirmed two serious limitations of the device for snow measurements. First, the path length is difficult to restrict to the specified range, i.e. 4-7/8 to 5.0 in. No trial run can be made to determine path length because the surface is thereby disturbed so that repeated tests under identical test conditions are nearly impossible to make. Second, and perhaps most damning, a true measure of frictional force is impossible because some snow is sheared from the mass and thrown out by the pendulum slider. Laboratory tests were conducted by sifting 1-1/2 in. of snow onto each test pavement, compacting to 3/4-in. depth, and making five or more pendulum swings, each on an undisturbed snow surface. Comparison runs using the SFG were made under identical conditions; the results are presented in Figure 14. It is apparent that scatter is somewhat greater with the British Portable Tester, but more significant is the entirely different ordering of high and low friction surfaces. The British Portable Tester showed the dense-graded asphaltic concrete to have the highest friction, whereas the SFB gave the lowest friction values for this pavement. A clear trend of DGA-OGA-PCC in order of increasing surface friction gauge values was found, but the British Portable Tester trend is not only opposite but differs in the ordering of OGA and PCC.

## EXPERIMENTAL RESULTS

The friction tests made with the surface friction gauge represent a locked wheel skid condition except

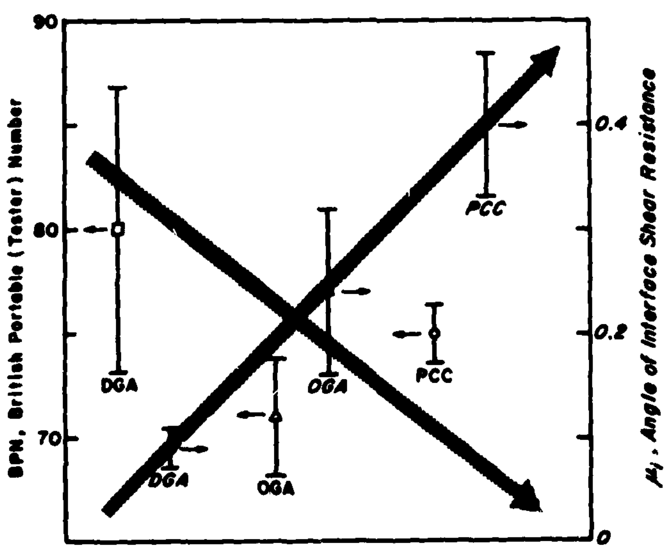
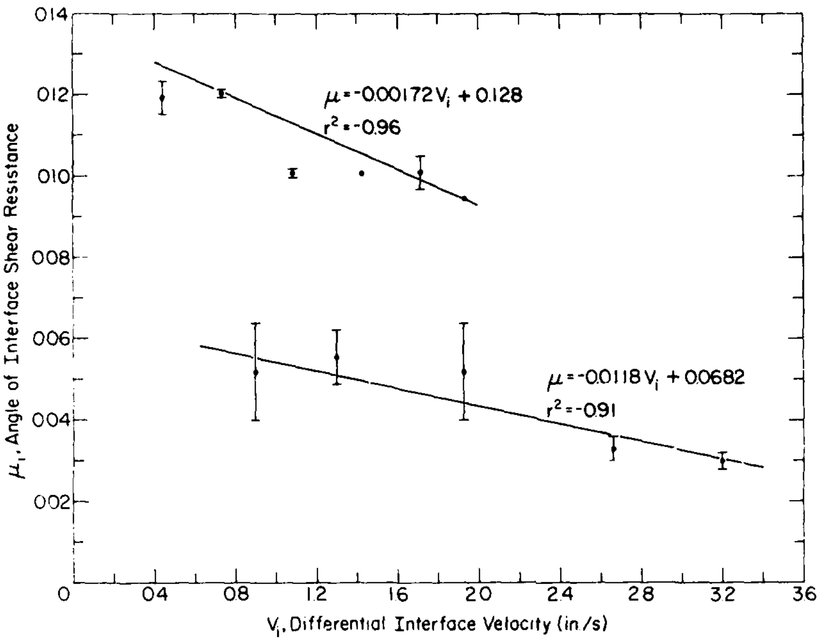
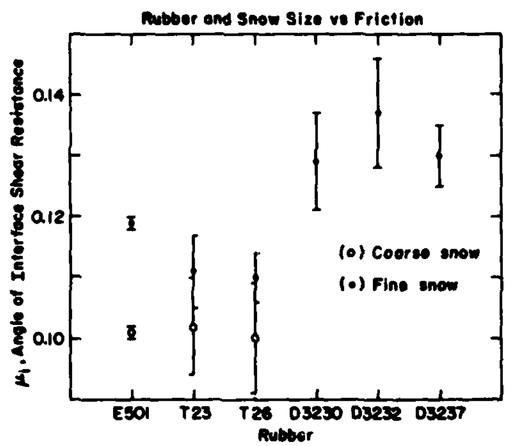



*Figure 14. Comparison of the coefficient of friction values obtained with the surface friction gauge and the British Portable Tester numbers; note the roughly orthogonal ordering of the DGA/OGA/PCC relationship.*




*a. Differential interface velocity.*




*b. Tire rubber types and snow grain size.*

*Figure 15. Variation of coefficient of friction with interfacial velocity (sliding velocity) with two significant parameters at 30°F, surface friction gauge data. Coarse snow was sieved through 2.38-mm openings, and fine snow through 1.2-mm openings. Error bars represent ±1 standard deviation.*

that the same surface is scoured during the test and no energy is absorbed by surface deformation following the initial compaction. A slipping wheel, in contrast, is continually contacting a different surface which may undergo compaction. The thermal regimes are also different since frictional heat is not dissipated rapidly in the case of the rotating annulus, whereas the rotating tire will more closely approximate the temperature of the air. That the heat of friction generated by the rotating rubber annulus is of significance is borne out by Figure 15a, which relates angle of interface shearing resistance $\mu_i$ to the interfacial velocity

between rubber and ice. The rate of change of $\mu_i$ with interfacial velocity is greater with ice than with snow, as one would predict because of the greater number of contacts between the sliding surfaces. The observation is amplified by the differences in $\mu_i$ with snow grain size (Fig. 15b): coarse snow (sieved through 2.38-mm openings) allows fewer points of contact on the rubber surface, and therefore a lower $\mu_i$ is measured than with fine snow (sieved through 1.2-mm openings). However, the cohesion of the snow will also affect the value of $\mu_i$.

Figure 15b also demonstrates the large effect rubber formulation has on $\mu_i$. Since the compositions of all rubbers except the ASTM E501 were not determined for these tests, no conclusion can be reached regarding the cause of the different frictional values (the rubbers were provided by Armstrong Rubber Company and represent experimental formulations of winter tread rubber). It is interesting, however, that the E501 rubber gave the most consistent results. These tests were all conducted at the same temperature (-1.1°C, 30°F) and interfacial velocity. Snow temperature, of course, can be expected to affect $\mu_i$ because of its influence on intergranular bond strength; Figure 16 shows that as temperature drops, $\mu_i$ increases, as predicted. Initial, uncompacted snow depth in all these tests was 1-1/8 in., which compacted to approximately 7/8 in. under the annulus load. Even with this depth, the type of pavement on which the snow lies has a slight effect on the initial frictional measurement (Fig. 17), suggesting that the snow is shearing and therefore is being influenced by the roughness of the snow/pavement interface.

The change in angle of interfacial shearing resistance following the application of salt on snow at the rate of 300 lb/LM is shown in Figures 17a-17c for the three pavements and at the three test temperatures. Each pavement type shows a characteristic response:

1. Open-graded asphaltic concrete (Fig. 17a)
   a. at 30°F an initial rapid increase in $\mu_i$ is followed by only a slight increase to the final (300-min) value.
   b. at 20°F only a small increase in $\mu_i$ occurs initially, and the final value does not change significantly from the value 1/3 through the test.
   c. at 10°F a sharp drop in initial $\mu_i$ is followed by a gradual decrease.
2. Dense-graded asphaltic concrete (Fig. 17b)
   a. at 30°F $\mu_i$ increases rapidly following salt application and continues a fluctuating increase.

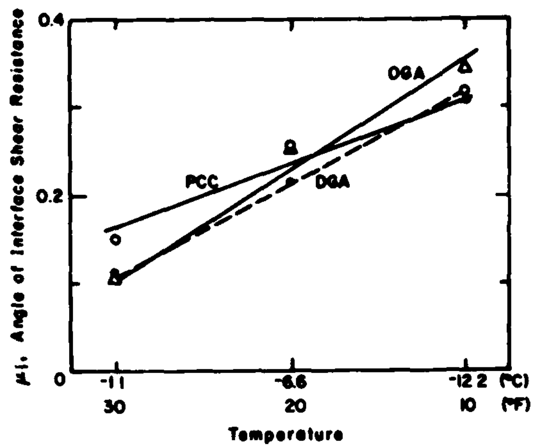
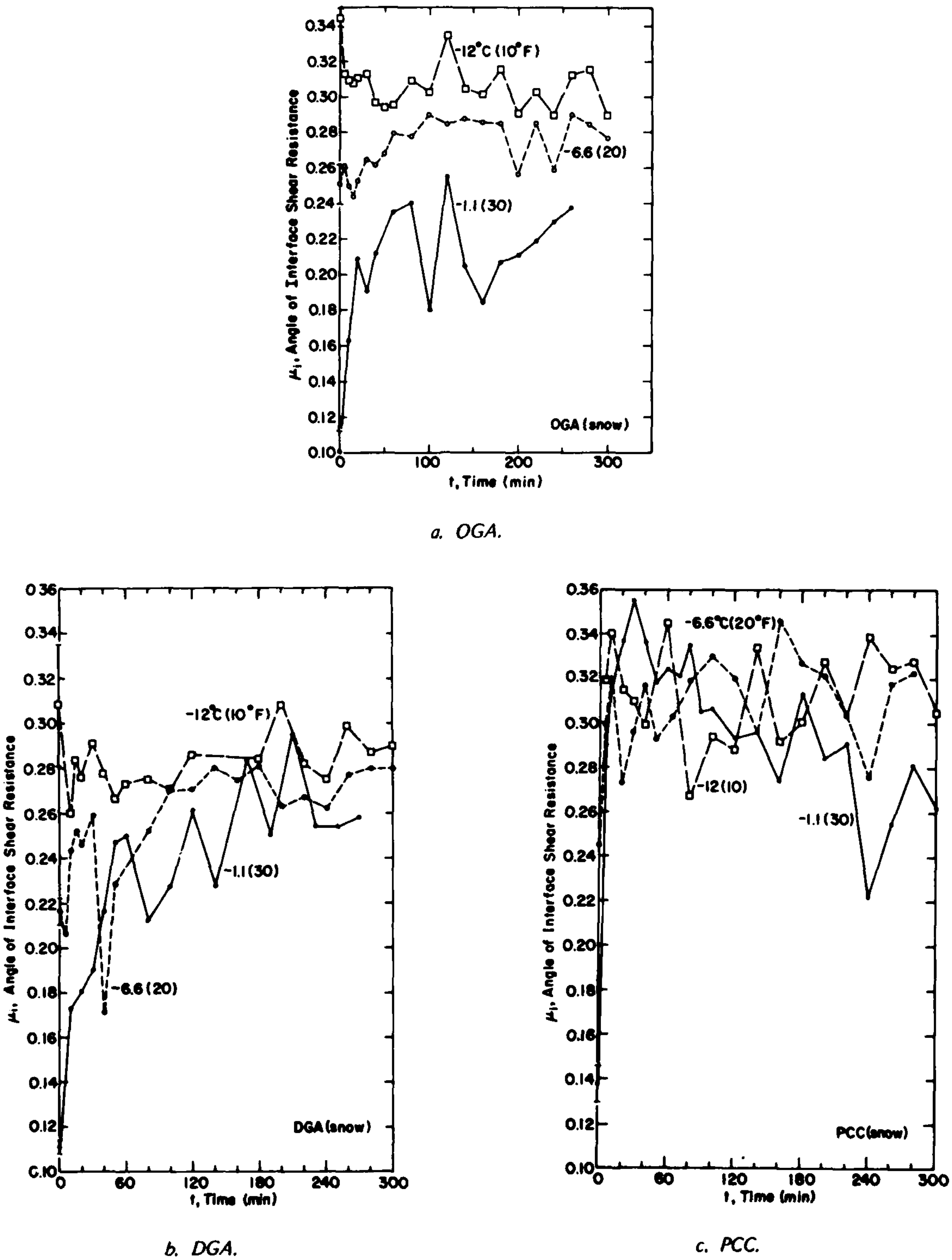



*Figure 16. Influence of temperature on coefficient of friction between rubber and snow for three pavement types, sliding speed 1.64 in./s, surface friction gauge data.*

   b. at 20°F rapid net increase in $\mu_i$ until about 1/3 through the test when it becomes nearly constant.
   c. at 10°F initial drop in $\mu_i$ followed by a slight net increase, but the ending value ($t$ = 300 min) remains lower than value before salt application.
3. Portland cement concrete (Fig. 17c)
   a. at 30°F rapid increase in $\mu_i$ was followed by a gradual drop in $\mu_i$.
   b. at 20°F rapid increase in $\mu_i$ followed by nearly constant $\mu_i$.
   c. at 10°F essentially no change in $\mu_i$.

All three pavements showed the lowest $\mu_i$ at 30°F at the conclusion of the 300-min test period compared to the other test temperatures. For the untrafficked case we can conclude that application of salt on snow at temperatures of 20°F or lower, with no solar radiation incident on the surface, will either have little effect on the angle of interface shearing resistance, or may decrease it slightly.

Results of tests run with the surface friction gauge on salt-treated ice-covered pavements are plotted in Figures 18–22. Figure 18 contrasts the angle of interface shearing resistance of snow and ice on the same pavement, open-graded asphaltic concrete. Starting from essentially the same value of $\mu_i$ for the untreated surface, $\mu_i$ for snow increases more rapidly than for ice. This can be attributed to the drainage of the melt in the case of snow, whereas the melted ice largely remains in place even with a gradient across the pavement.




*a. OGA.*



*b. DGA.*

*c. PCC.*

*Figure 17. Change in coefficient of friction of rubber/snow on OGA, DGA and PCC asphaltic concrete following application of salt at rate of 300 lb/LM for three temperatures, surface friction gauge data.*

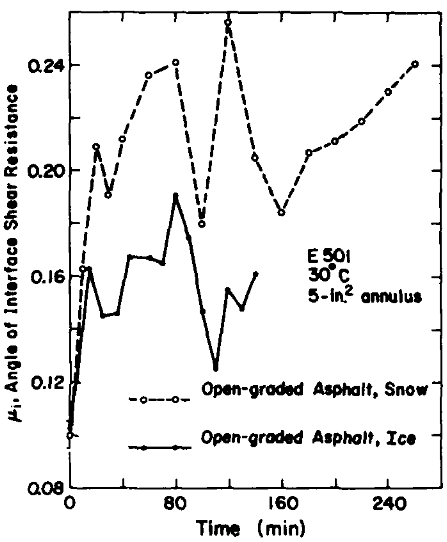



*Figure 18. Comparison of change of coefficient of friction on open-graded asphaltic concrete following salt application at rate of 300 lb/LM on both snow and ice, air temperature 30° F, surface friction gauge data.*

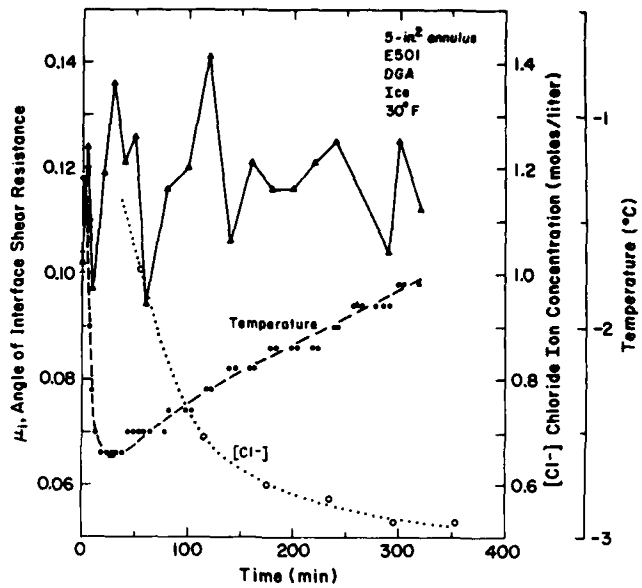



*Figure 19. Variation of coefficient of friction, pavement surface temperature and chloride ion concentration following application of salt on ice at rate of 300 lb/LM on dense-graded asphaltic concrete, air temperature 30° F, surface friction gauge data.*

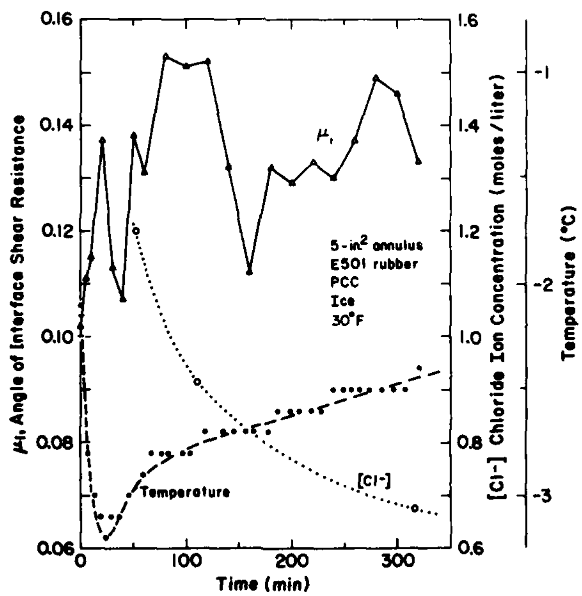



*Figure 20. Variation of coefficient of friction, pavement surface temperature, and chloride ion concentration following application of salt on ice at rate of 300 lb/LM on portland cement concrete, air temperature 30° F, surface friction gauge data.*

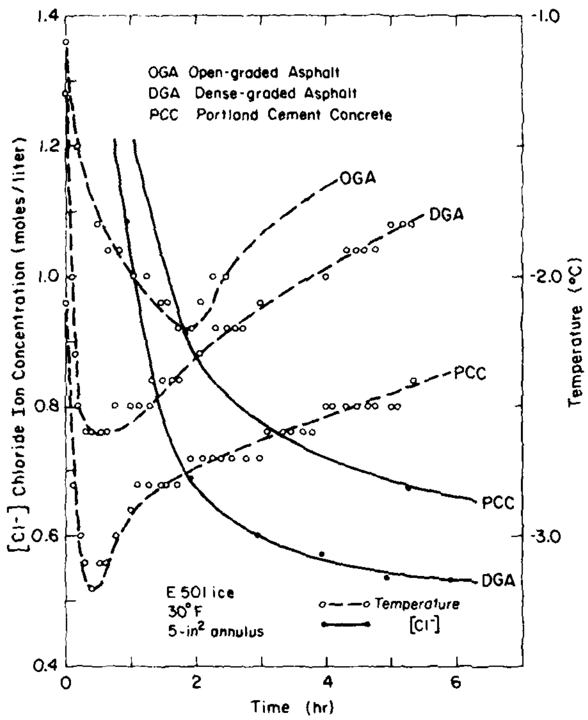



*Figure 21. Comparison of change in chloride concentration and pavement surface temperature for three pavement types following application of salt at rate of 300 lb/LM, air temperature 30°F, surface friction gauge data.*

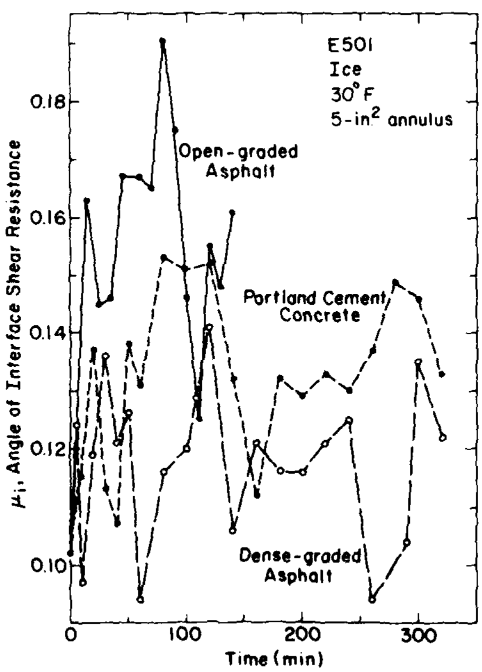



*Figure 22. Comparison of variation of coefficient of friction for three pavement types following application of salt on ice at rate of 300 lb/LM, air temperature 30°F, surface friction gauge data.*

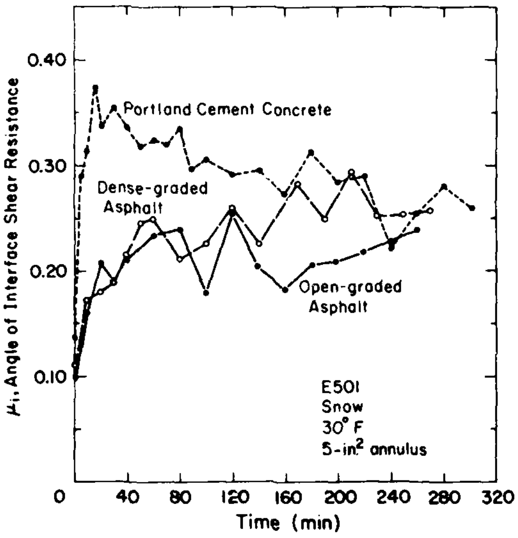



*Figure 23. Comparison of variation in coefficient of friction for three pavement types following application of salt on snow at rate of 300 lb/LM, air temperature 30°F, surface friction gauge data.*

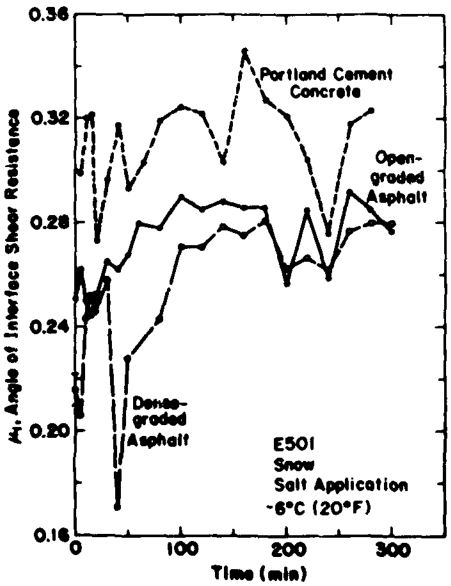



*Figure 24. Comparison of variation in coefficient of friction for three pavement types following application of salt on snow at rate of 300 lb/LM, air temperature 20°F, surface friction gauge data.*

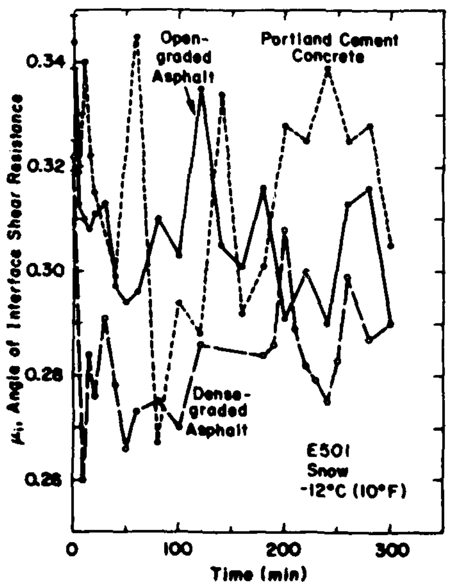



*Figure 25. Comparison of variation in coefficient of friction for three pavement types following application of salt on snow at rate of 300 lb/LM, air temperature 10°F, surface friction gauge data.*

Both dense-graded asphaltic concrete and portland cement concrete show more pronounced drops in $\mu_i$ following an initial rise than does the open-graded asphaltic concrete (Fig. 18-20). Comparison of the pavement temperatures for the three pavements (Fig. 21) suggests this as a *contributing factor:* the reduction in temperature of the pavement surface resulting from absorption of thermal energy to melt the ice is greater and occurs more rapidly in the case of PCC and DGA. Though the chloride ion concentrations of PCC and DGA are inversely related to the pavement temperature change (less salt will dissolve at the lower temperature), the relationship could not be determined for OGA since rapid drainage through the porous surface prevented sampling. Nonetheless, the lesser pavement cooling and the melt drainage might be expected to result in higher friction for OGA, and Figure 22 confirms this. The influence of temperature cannot be cited as having the same influence on the change of $\mu_i$ for DGA and PCC, however, for PCC develops higher values of $\mu_i$ even though it is colder than DGA.

These data are replotted in Figures 23-25 to compare $\mu_i$ on the three pavements at each temperature. At 30°F, the change in $\mu_i$ for both types of asphaltic concrete approximately track one another and end very close together. Portland cement concrete $\mu_i$ increases very rapidly but then decreases to a value nearly equal to the two asphaltic concretes at the test conclusion ($t$ = 300 min). Portland cement concrete has significantly higher $\mu_i$ values for $t$ = 300 min at both 20°F and 10°F during nearly 2/3 of the test period, but the gap then closes. Again it should be emphasized that the snow surfaces were not trafficked.

The slipping wheel tests on the circular track were performed mainly on snow because of the major effect of trafficking on a compressible material. As benchmarks, however, both brine and freshwater films were sprayed on the pavements and the angle of interface shearing resistance of the slipping wheel was measured at two temperatures, 60°F (15°C) and 31°F (-1°C). (Brine concentration was equivalent to 300 lb/LM applied to 1 in. of snow of 6 lb/ft$^3$ [0.1 g/cm$^3$] density). The values of $\mu_i$ are uniformly low, but the most interesting result is the lack of significant differences due to brine or plain water for a specific temperature (Fig. 26). Temperature did affect $\mu_i$, though, increasing it at a higher temperature for all the pavements, with a ranking of high to low $\mu_i$ values of DGA-PCC-OGA. At the lower temperature, the ranking is less significant, but OGA appears to have slightly lower values of $\mu_i$ than DGA and PCC, which are nearly the same. High variability in the test results led to the abandonment of a proposed fractional factorial experimental design since replication was considered necessary to obtain statistically significant values. Each test required considerable time to prepare the 9-ft$^2$ snow cover on each pavement (sieved to a depth of 1/2 in.) to run the test, to clean off any salt residue to avoid contamination, and finally to remove residual water by vacuuming before it could freeze. From two to six replicates were used for temperatures of 30°F and 20°F and the three salt application rates of 100, 300, and 500 lb/LM, but only two tests were run at 10°F, using an application rate of 300 lb/LM.

Mean values of $\mu_i$ and the regression curves as a function of time after salt application are given in Figures 27-29 for dense-graded asphaltic concrete, the two (or three) test temperatures, and the three salt application rates. Similar graphs are presented for portland cement concrete (Fig. 30-32), and open-graded asphaltic concrete (Fig. 33-35). The same data are replotted in Figures 36-38 to compare the three pavements on the basis of an application rate/temperature combination. It is readily apparent that an application rate of 100 lb/LM is *insufficient to increase* $\mu_i$ rapidly, and that the final (60-min) values do not approach the values for brine (Fig. 36a). The effect is similar for all three pavements. At the same temperature of 30°F, though, an application rate of 300 lb/LM brings about a rapid change in $\mu_i$ for PCC and DGA, with the final (60 min) values approaching (DGA) or *exceeding* (PCC) the brine values (Fig. 36b). OGA responds quite differently; its $\mu_i$ does not change with time following salt application. At an application rate of 500 lb/LM, PCC and DGA data are not remarkably different from those for the 300-lb/LM rate (Fig. 36c), but OGA now shows an increase in $\mu_i$ very similar to that of the other two pavements. The response of OGA at 20°F for the lowest application rate (Fig. 33) is unexpected. We conjecture that the lesser melting of the snow at the lower temperature reduced the drainage through the porous surface, and the undissolved salt remaining on the surface functioned as an abrasive to increase the coefficient of friction. Comparison of the OGA 300-lb/LM (Fig. 34) and 500-lb/LM (Fig. 35) application rates lends some support to this hypothesis, though one might expect a higher $\mu_i$ at 10°F than at 20°F instead of the reverse (Fig. 34). No independent test of this hypothesis was made. Both DGA and PCC show a *more regular increase* in $\mu_i$ with temperature, but only for the first 20 to 40 min of trafficking after salt application.

Typical pavement surfaces at the conclusion of 60-min tests are shown for all three pavements and for the 100-lb/LM application rate (Fig. 39) and 300 lb/LM (Fig. 40), all at 30°F.

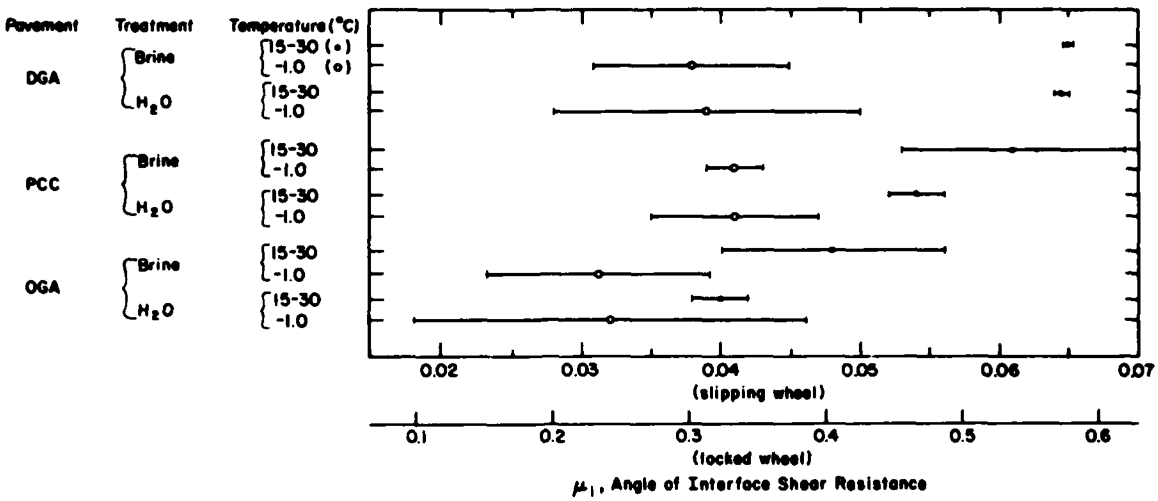



*Figure 26. Coefficient of friction developed between slipping test tire and three pavements with surface films of brine and water at two temperatures. Error bars are ± 1 standard deviation.*

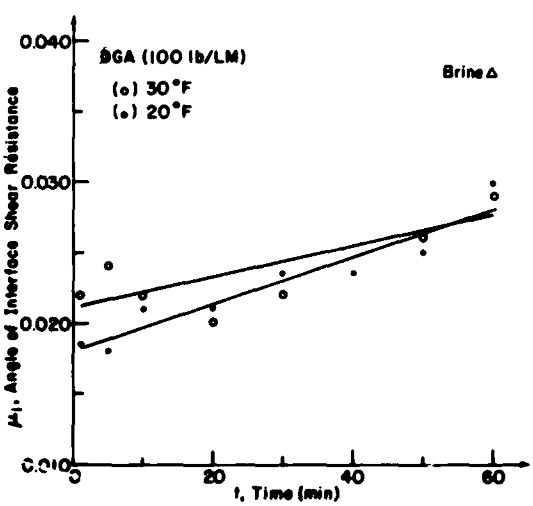



*Figure 27. Coefficient of friction change with time, trafficking tests, on dense-graded asphalt, 100 lb/LM, for two temperatures.*

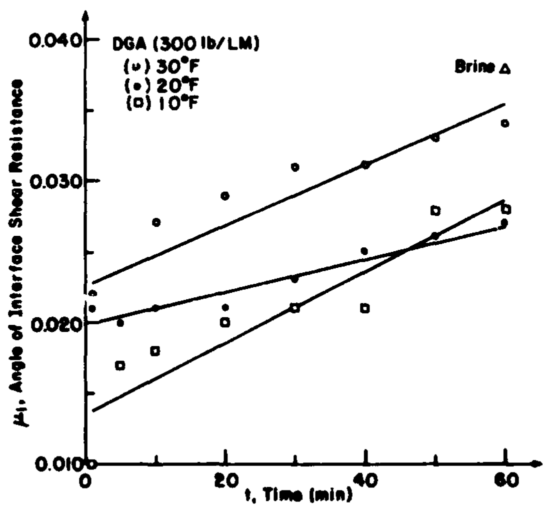



*Figure 28. Coefficient of friction change with time, trafficking tests on dense-graded asphalt, 300 lb/LM, for three temperatures.*

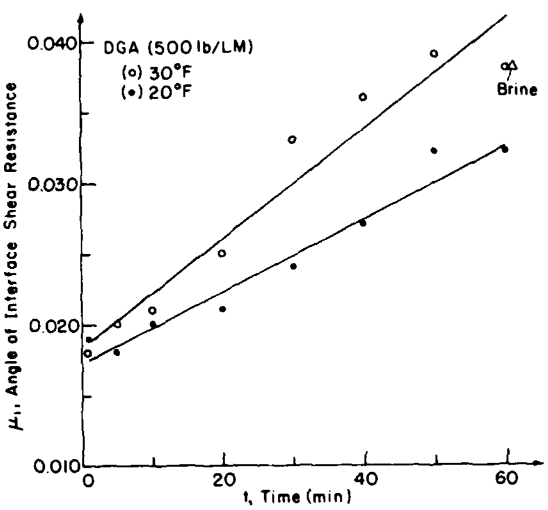



*Figure 29. Coefficient of friction change with time, trafficking tests on dense-graded asphalt, 500 lb/LM, for two temperatures.*

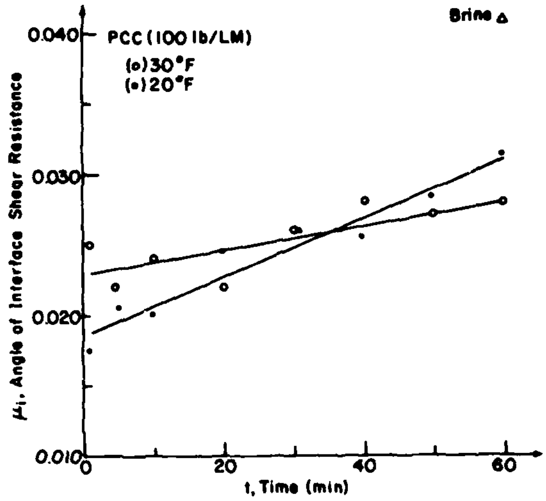



*Figure 30. Coefficient of friction change with time, trafficking tests on portland cement concrete, 100 lb/LM, for two temperatures.*

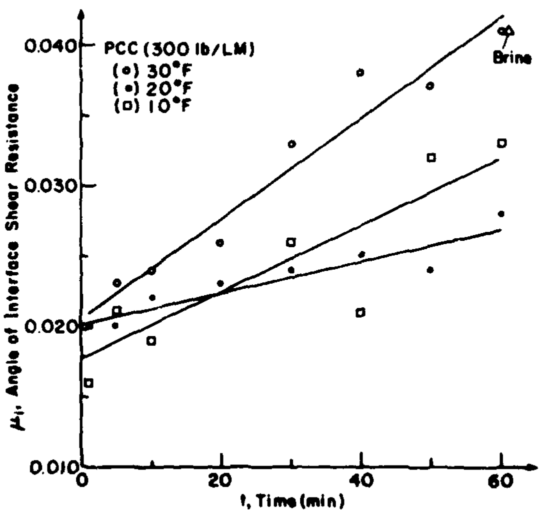



*Figure 31. Coefficient of friction change with time, trafficking tests on portland cement concrete, 300 lb/LM, for three temperatures.*

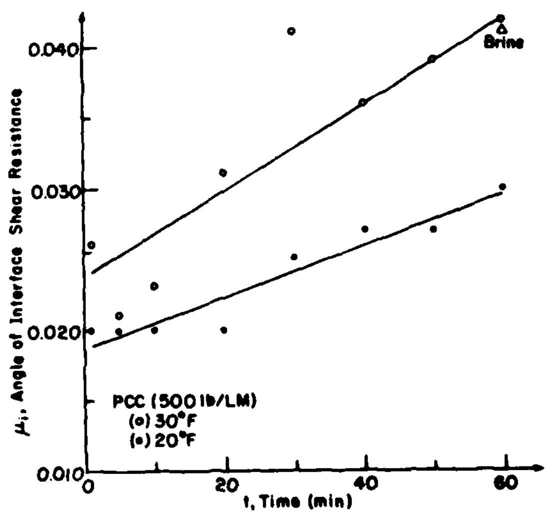



*Figure 32. Coefficient of friction change with time, trafficking tests on portland cement concrete, 500 lb/LM, for three temperatures.*

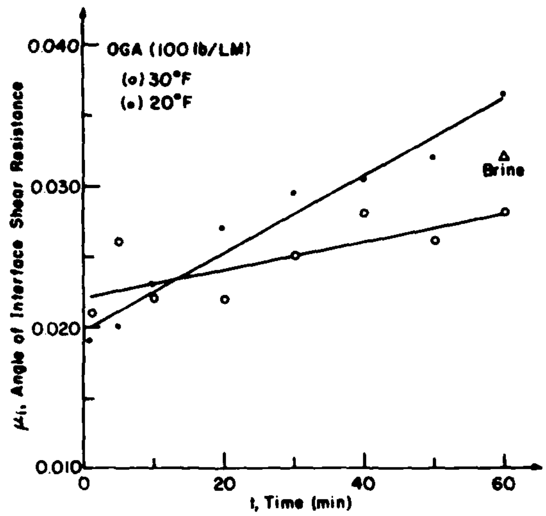



*Figure 33. Coefficient of friction change with time, trafficking tests on open-graded asphaltic concrete, 100 lb/LM, for two temperatures.*

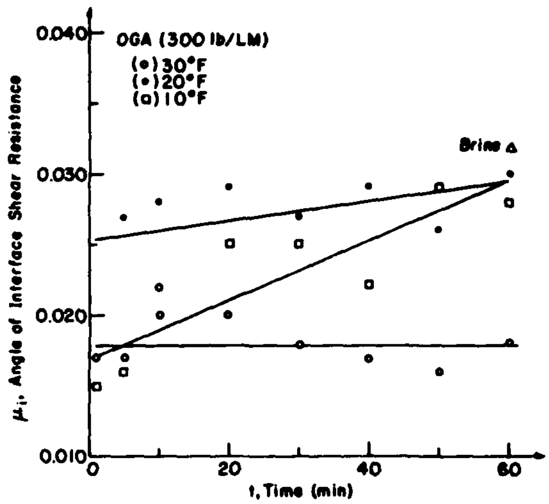



*Figure 34. Coefficient of friction change with time, trafficking tests on open-graded asphaltic concrete, 300 lb/LM, for three temperatures.*

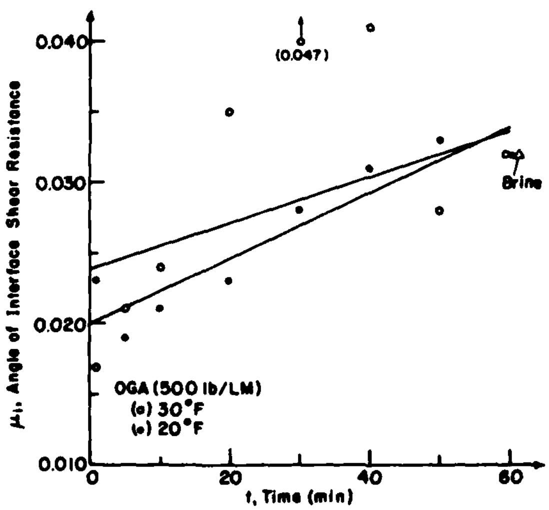
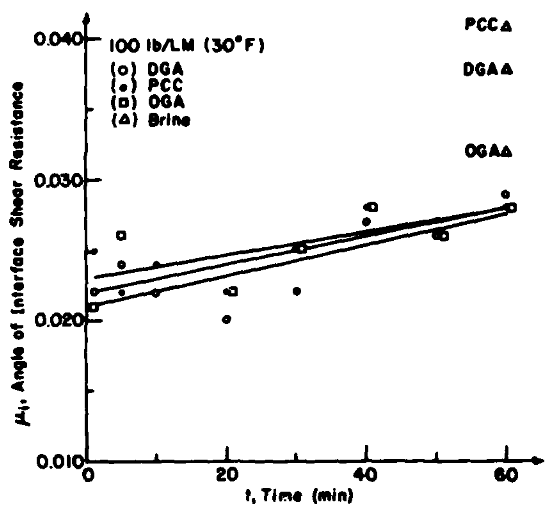
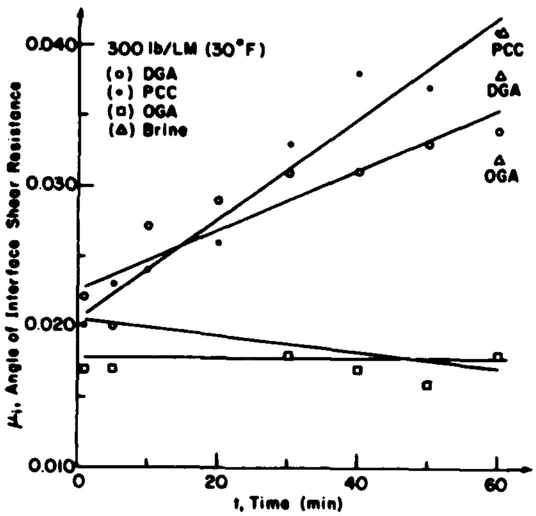



*Figure 35. Coefficient of friction change with time, trafficking tests on open-graded asphaltic concrete, 500 lb/LM, for two temperatures.*

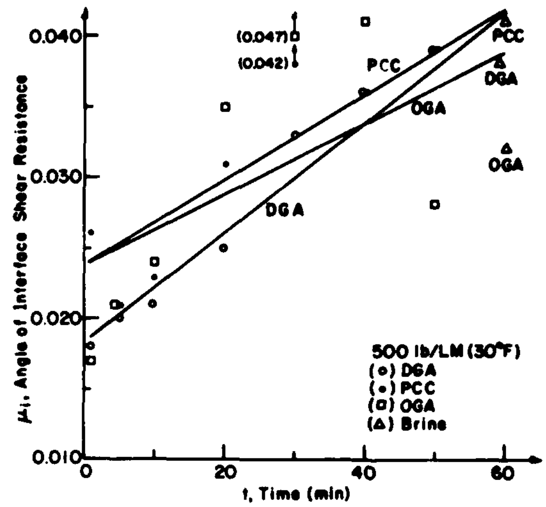



*a. 100 lb/LM*

*Figure 36. Comparison of variations in coefficient of friction, after salt application and for brine on three types of pavements, 100, 300 and 500 lb/LM at 30°F.*

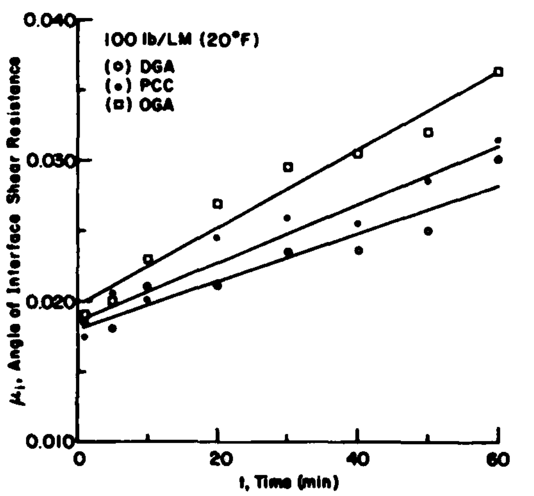



b. 300 lb/LM

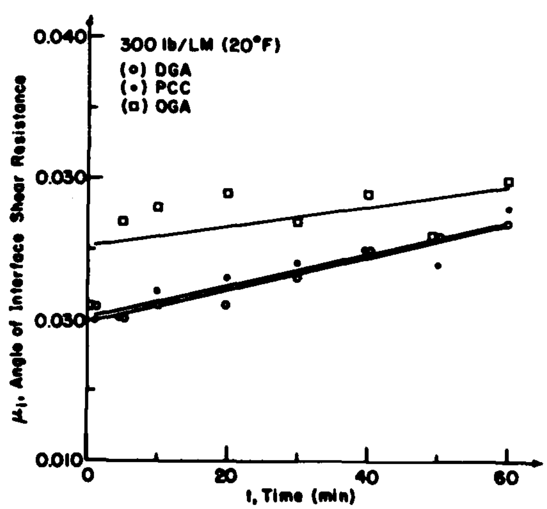



c. 500 lb/LM

Figure 36. (Cont'd).

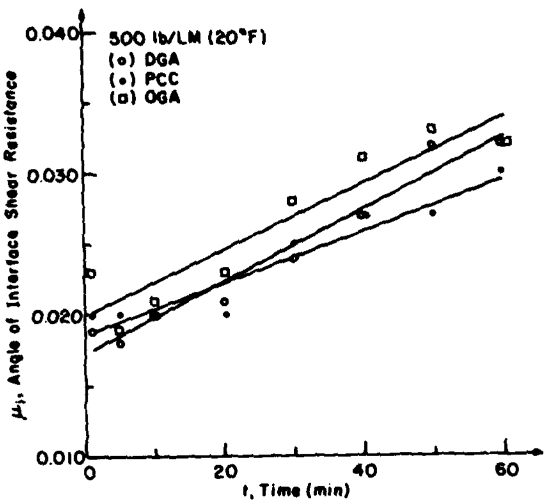



a. 100 lb/LM




b. 300 lb/LM

Figure 37. Comparison of variations in coefficient of friction after salt application on three types of pavements, 100, 300 and 500 lb/LM at 20°F.




c. 500 lb/LM

Figure 37 (Cont'd). Comparison of variations in coefficient of friction after salt application on three types of pavements, 100, 300 and 500 lb/LM at 20°F.

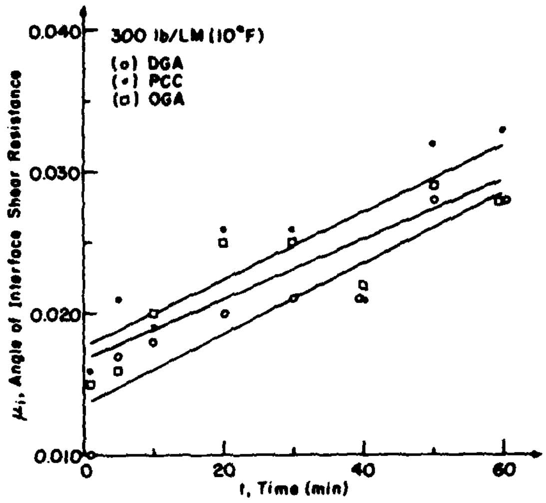



Figure 38. Comparison of variations in coefficient of friction after salt application on three types of pavements, 300 lb/LM at 10°F.


a. DGA.

Figure 39. Surface of DGA, PCC and OGA following 60-min test, 100 lb/LM salt application rate, 30°F.


*b. PCC.*

*c. OGA.*

*Figure 39 (Cont'd).*

It was impossible to obtain intermediate values of $\mu_i$ with the surface friction gauge during a test on the circular track because trafficking was uninterrupted. Only a direct comparison of values of the surfaces prior to salt application and of the brine covered surfaces is possible (Table 2).

**Table 2 Angle of interfacial shearing resistance, $\mu_i$.**

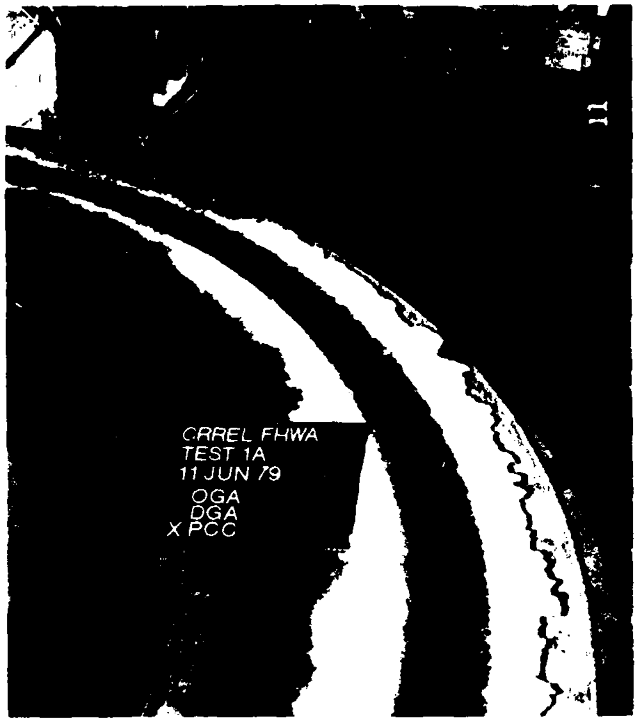
| | *DGA* | *PCC* | *OGA* |
|---|---|---|---|
| Brine (31°F) | | | |
| SFC | 0.295 | 0.277 | 0.200 |
| Track | 0.038 | 0.041 | 0.032 |
| SFG/track | 7.76 | 6.76 | 6.25 |
| Snow (300 lb/LM, 30°F) | | | |
| SFG | 0.111 | 0.138 | 0.100 |
| Track | 0.020 | 0.023 | 0.019 |
| SFG/track | 5.50 | 6.00 | 5.26 |

Measurements of friction by locked-wheel or slipping-wheel modes have shown a high degree of correlation on pavements not covered by snow or ice (Shah and Henry 1977). Though correlation of these methods on snow or ice cannot be expected to be as close for the reasons cited earlier, $\mu_i$ values obtained by the two devices used in these tests are plotted in Figure 41 to provide an operational method of selecting the application rate necessary to result in a desired $\mu_i$ in a specified time. The same information is presented in another form which may be more useful for operators (Fig. 42 and 43). Here the application rate is plotted as a function of $\mu_i$ with the parameter of reaction time (for 10, 30, and 60 minutes).

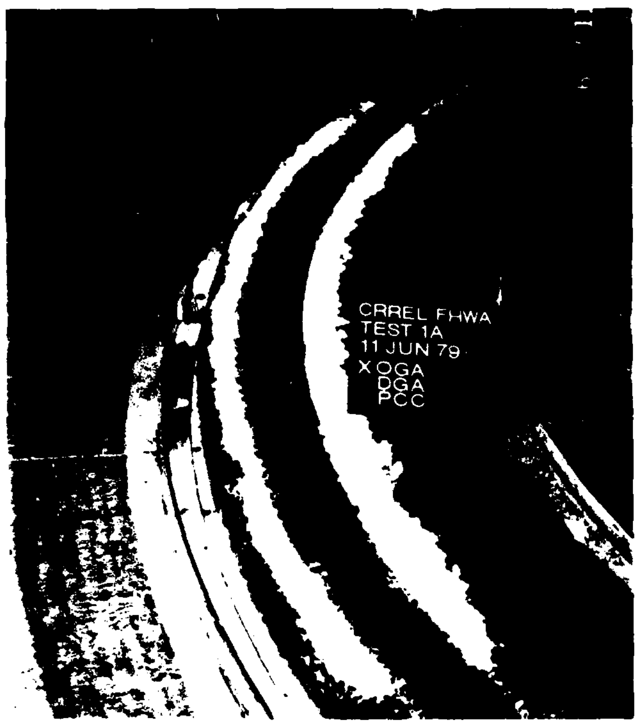
An application rate of about 100 lb/LM of salt on snow-covered PCC is insufficient to obtain an increase of $\mu_i$ within 60 min, as demonstrated both by laboratory tests and in the Penn State field tests (19 February, 5 March dates). An application rate of 250-300 lb/LM on PCC will significantly increase friction after one hour (350 wheel passes), as determined in laboratory tests. It required nearly 3 1/2 hours to reach a similar friction value in the Penn State field tests (5 March) for an application rate of 250 lb/LM but only about 60 min for an application rate of 375 lb/LM. Trafficking of the bituminous concrete on the Penn State test track was with a 7-axle truck, and therefore cannot be compared with the results for PCC.

*a. DGA.*

*Figure 40. DGA, PCC and OGA following 60 min. test, 300-lb/LM salt application rate, 30°F.*

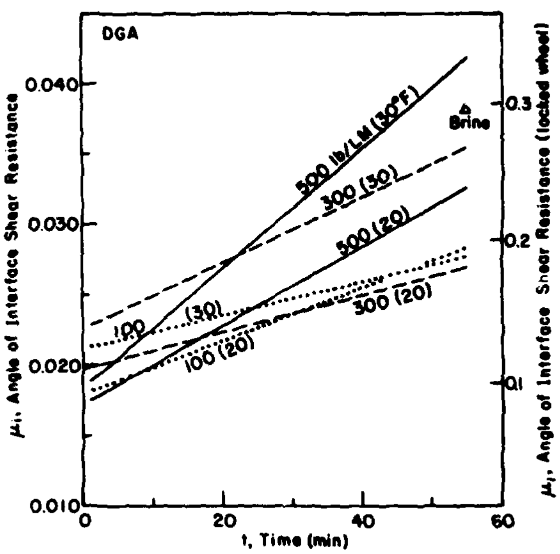



*b. PCC.*

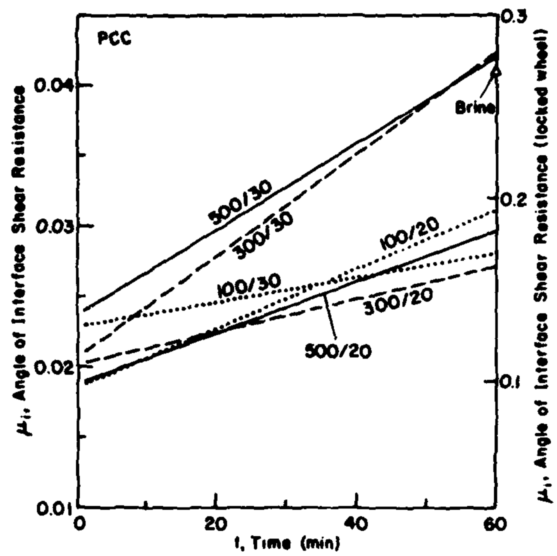



*c. OGA.*

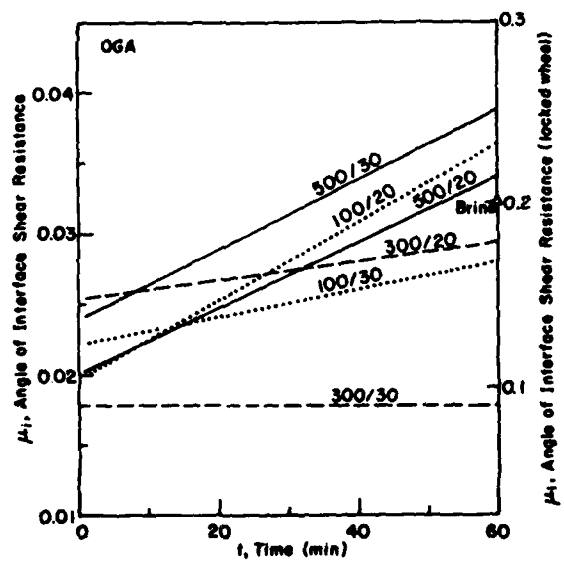
*Figure 40 (Cont'd).*




*a. DGA.*

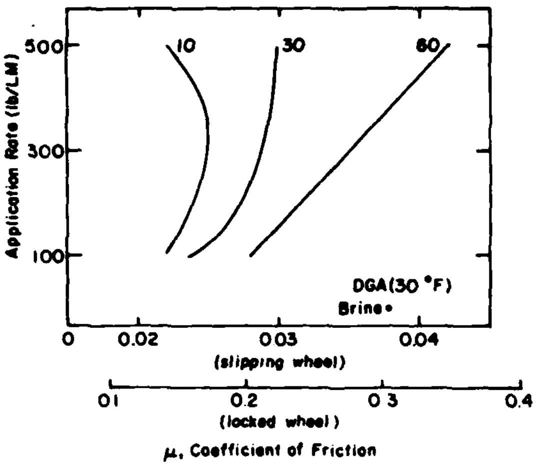



*b. PCC.*

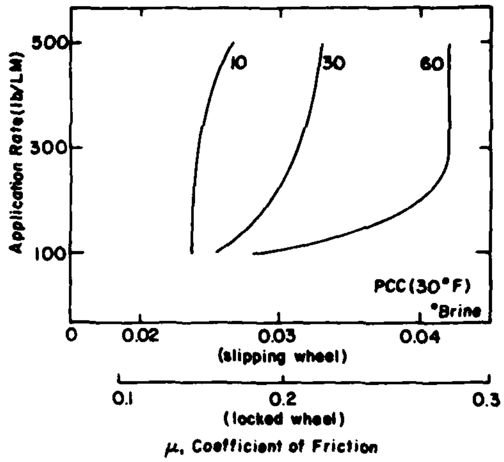



*c. OGA.*

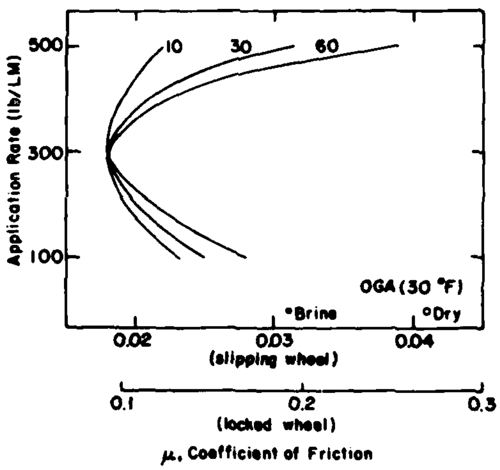
*Figure 41. Charts for selecting application rate on DGA, PCC and OGA concrete, given required value of coefficient of friction in specified time and air temperature.*




*a. DGA.*

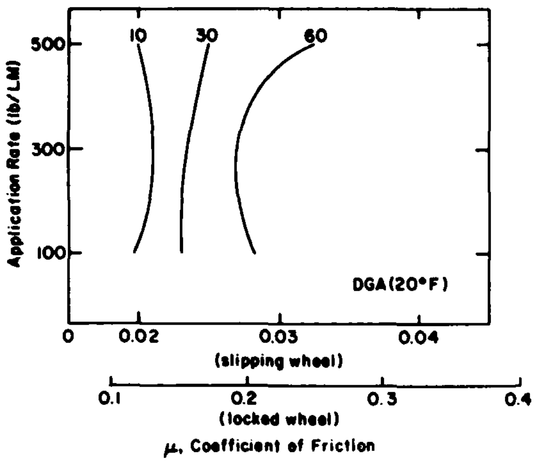



*b. PCC.*

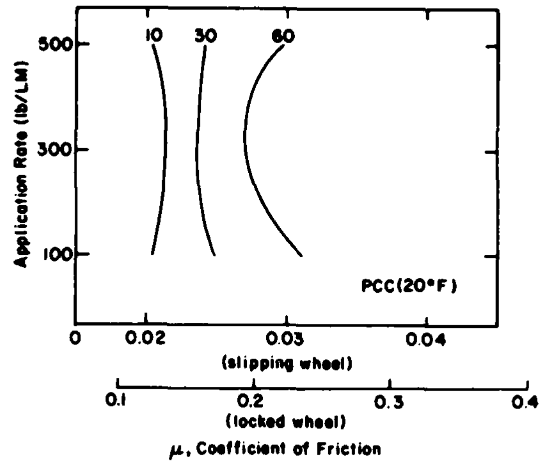



*c. OGA.*

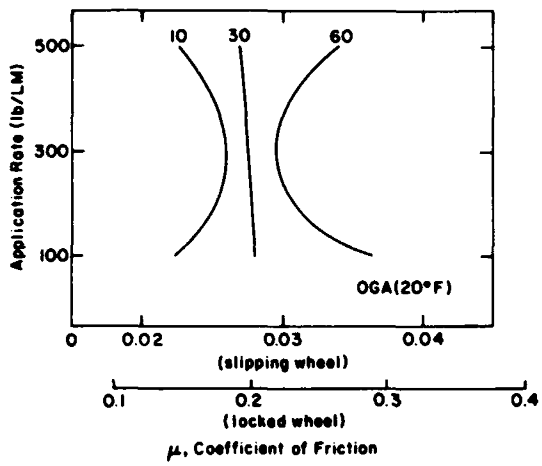
*Figure 42. Charts for selecting application rate on DGA, PCC and OGA concrete for reaction times of 10, 30, and 60 minutes at 30° F.*




*a. DGA.*




*b. PCC.*




*c. OGA.*

*Figure 43. Charts for selecting application rate for DGA, PCC and OGA for reaction times of 10, 30, and 60 minutes at 20°F.*

## CONCLUSIONS

The use of the coefficient of friction (referred to as the angle of interface shearing resistance $\mu_i$) developed between rubber and a snow- or ice-covered surface is an objective measure of the change in surface properties following the application of sodium chloride as a deicing chemical. Two devices have been designed, built, and tested for providing measures of surface friction. One device, the surface friction gauge, is a rotating rubber annulus which measures the friction under a normal force in terms of the increase in torque during rotation while in contact with the surface. The other is a modified electric garden tractor on which is mounted a test tire that rotates at a constant slip rate by mechanical gearing to its rear drive wheel. A low slip rate (15-25%) is desirable while trafficking a short test track in order to prevent rapid destruction of the snow cover. This condition will simulate that on a road not subjected to frequent vehicle braking or accelerating such as would occur at a traffic signal; it corresponds, in other words, to the greatest amount of road mileage receiving snow and ice control. Measurement of surface friction over an extensive test section that receives multi-path compaction would not be subject to this limitation, and a locked wheel mode could be used satisfactorily.

Open-graded asphaltic concrete shows consistently lower friction values than do the other two pavement types at a temperature near the melting point. At the two lower test temperatures, however, OGA either has higher initial friction values, or its friction increases more rapidly than on the other two pavements following salt application. Both PCC and DGA show consistently higher $\mu_i$ values at 30°F than at 20°F

for the trafficked surface. The untrafficked surface shows an increase in $\mu_i$ for all pavements with reduced temperature (Fig. 16).

The optimum application rate of salt on PCC and DGA lies between 100 and 300 lb/LM, with the higher rate necessary for a rapid increase in friction. An application rate of 500 lb/LM on PCC and DGA resulted in slight or no improvement in $\mu_i$. OGA responds very differently: a rate of 300 lb/LM at 30°F resulted in reduced $\mu_i$, and both 100 and 500 lb/LM rates improved $\mu_i$. At a temperature of 20°F, there is no great difference in $\mu_i$ for all three application rates, but again the 300 lb/LM rate shows a slightly lower $\mu_i$.

## RECOMMENDATIONS

Laboratory tests have shown the change of friction with time after salting under controlled, idealized conditions. Even under laboratory conditions the variability is high since the properties of snow that affect the changing friction also vary over a wide range. Only a limited set of parameters could be included in the test program; in particular, the number of wheel passes was low compared to the expected number on a major traffic artery. The test results can be applied, however, if the friction value required for a given condition is known, i.e. the minimum value required to achieve some objective such as stopping a vehicle (truck, sedan, etc.) in a given distance or negotiating a hill of a specified grade with a truck (sedan) from a standing start or at a constant speed. The most effective and efficient technique for accumulating the extensive data necessary to arrive at recommended minimum $\mu_i$ values is by use of a continuously recording skid tester. A skid trailer is undesirable because of reduced maneuverability and the extra hazard a trailer represents on a slippery pavement.

Two skid vehicles have been developed which would make suitable test devices: the Saab Friction-Tester, and the 4-wheel drive instrumen[illegible] test bed designed by Henry Hodges, Nevada Automotive Test Center, Reno, Nevada. The former uses an instrumented wheel mounted between the rear wheels just behind the rear axle so that continuous slip force measurements can be made. Three machines of the second type have been built by Hodges, one of which remains at the Nevada Automotive Test Center, one which is now owned by CRREL, and one which is owned by National Highway Traffic Safety Administration. They are all essentially similar, and can be operated with one axle driving and the other braking; forces on the instrumented wheels are measured with triaxial load cells on the axles. These self-contained friction testers can be operated at normal traffic speeds. They would provide a rapid method of obtaining data either on a controlled test pavement, or on a publicly traveled road where the required observations of ADT, salt application time and rate, and meteorological parameters can be made. It is highly advisable, if not essential, that all data acquisition be digitized since a large number of experimental replications are necessary in order to reduce the variance inherent in measuring a material such as snow.

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## APPENDIX A. TEST PAVEMENTS

The three pavements used in the tests were dense-graded asphaltic concrete (DGA), open-graded asphaltic concrete (OGA), and portland cement concrete (PCC). The two asphaltic concretes were mixed and placed in the test pavement forms at the West Lebanon, New Hampshire, plant of Pike Industries. The circular track sections were 13½-ft outside diameter, 10½-ft inside diameter, and 2 in. deep, requiring nearly 9.5 $ft^3$ for each pavement. Rolled aluminum angle was used as forms (Fig. A1). DGA was used as the base for the OGA. The DGA was compacted with a sidewalk roller for the final compaction, but hand compaction was necessary for the base of the 2-x 5-ft test sections used for the surface friction gauge (Fig. A2). Following compaction, the asphaltic concrete circular track sections were moved to CRREL's large 2-story coldroom and placed on a plywood platform. The circle was completed with the aluminum angles and then the PCC pavement was poured in place. The surface was given a light burlap drag finish followed by transverse fine grooving. Grooves were on 1/2-in. centers and were about 1/8 in. deep and 5/64 in. wide. Following wet burlap curing at a temperature of 70°F for over a month, the surface was treated with linseed oil diluted 1:1 with mineral spirits. The 2-x 5-ft PCC test pavement was cured only two weeks before it was moved into the coldroom, and testing was begun with the surface friction gauge.

New Hampshire specification was used for design of the portland cement concrete mix:

Class AA
4000 psi minimum compressive strength
28 days cured between 65 and 75°F
3/4 in. aggregate maximum
7 bags cement (minimum)/yd
Water-cement ratio 5 gal./bag
Air-entraining agent, 7 ± 1% entrained air
Slump 1-2 in.

Compressive strengths of 6-in.-diameter cylinders cured 28 days averaged 5955 psi. Vermont type III mix was used for the dense-graded asphaltic concrete. Maximum aggregate was 1/2 in., asphalt was 85-100 penetration, and mix temperature was 260°F. The open-graded asphaltic concrete friction course used as an overlay followed Vermont specification (Section 414) and conformed to the recommendations of Smith et al. (1974).

*Figure A1. Raking dense-graded asphaltic concrete in the rolled aluminum angle forms for the circular track test sections.*

*Figure A2. Hand compaction used for the base of the 2-x 5-ft asphaltic concrete test sections, followed by final compaction with a sidewalk roller.*

## APPENDIX B. PENNSYLVANIA STATE UNIVERSITY FIELD STUDY

G.F. Hayhoe and W. Benson

### INTRODUCTION

Tests were conducted to measure the response of ice- and snow-covered portland cement concrete pavement to combined salt application and vehicular trafficking. The snow surfaces were initially compacted by trafficking and the salt then applied at a known rate. Further trafficking was accompanied, at periodic intervals, by measurement of surface friction, collection of snow/snowmelt samples, and photographing of the surface.

### TEST SITES

Two locations were used: 1) the Pennsylvania Transportation Institute Skid Test Facility and 2) the State College By-pass. The Skid Test Facility is shown in Figure B1; the light transverse burlap drag section (5) and the transverse grooved portland cement concrete section (7) were used. Each section is 100 ft long x 6 ft wide. The test location on the State College By-pass is a new, unused section of four-lane divided highway with a transverse burlap drag portland cement concrete pavement (Fig. B2 and B3).

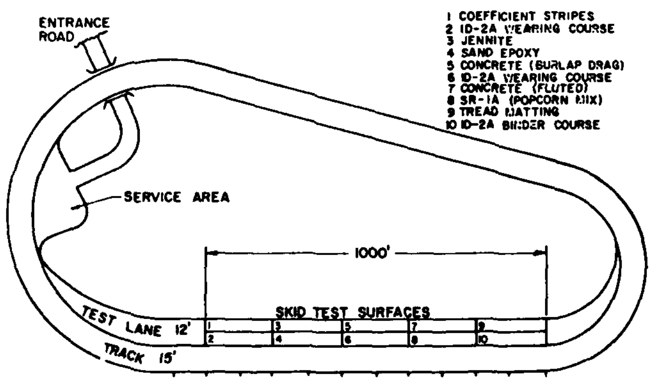


*Figure B1. The Pennsylvania Transportation Institute skid test facility.*

*Figure B2. Portion of the State College By-pass used for tests.*

*Figure B3. State College By-pass test section following completion of trafficking and skid testing.*

## TEST EQUIPMENT

*Friction measurement.* The frictional characteristics of the test surfaces were measured with the Penn State Mark II Road Friction Tester. This tester is a Chevrolet pick-up truck fitted with a single wheel, parallel linkage trailer. A pneumatic cylinder applies a load of 100 lbf to the trailer wheel during testing and can lift the wheel clear of the road when necessary. Friction force is measured by locking the trailer wheel and measuring the torque developed by the sliding tire. The test tire used in all of the tests was an ASTM E524 smooth-tread tire. Tread effects were thereby eliminated from the measurements and the test surface was relatively little affected by the friction measurements.

## SALT APPLICATION

Salt was spread on the test surfaces with a Cyclone Model 100 broadcast spreader designed to be pushed by hand. Initially, the spreader was hand operated, but this was found to be unsatisfactory because of occasional slipping of the drive wheel and because it was difficult to maintain constant speed in deep snow. The spreader was therefore mounted on the trailer of the road friction tester and the drive wheel loaded against the trailer wheel. By driving at constant speed, salt was spread from the rear of the tester at a uniform rate. Spreading speed was adjusted to spread salt over a 12-ft lane width. A more satisfactory method of spreading salt would have been to hire a motor-driven, truck-mounted spreader, but this was not possible because the severe snow storms that occurred at the beginning of the test period pressed all available units into service for clearing public roads.

The spreader was calibrated by filling the hopper with a weighed amount of salt, setting the feeder opening, driving the tester at the spreading speed over a known distance, and weighing the remaining salt. The salt application rate was then calculated from the weight of salt used and the distance traveled. The procedure was repeated at various settings of the feeder opening. At all times during testing and calibration the hopper was kept more than half full.

Commercial rock salt was used in the tests. A sieve analysis of a sample of the salt gave the results shown in Table B1.

**Table B1. Sieve analysis of a salt sample.**

| *Sieve size* | *Weight retained (g)* | *Percent retained* | *Cumulative percent retained* | *Cumulative percent passed* |
|---|---|---|---|---|
| 3/8 | 5.9 | 1.0 | 1.0 | 99.0 |
| No. 3 | 79.8 | 12.9 | 13.9 | 86.1 |
| No. 4 | 172.8 | 27.9 | 41.8 | 58.2 |
| No. 8 | 288.5 | 46.6 | 88.4 | 11.6 |
| No. 16 | 67.6 | 10.9 | 99.3 | 0.7 |
| Remainder | 4.5 | 0.7 | 100.0 | - |
| Totals | 619.1 | 100.0 | | |

## TEST PROCEDURE

Because tests to measure the response of snow surfaces to melting and trafficking had not previously been conducted at the Pennsylvania Transportation Institute, the test procedure was developed concurrently with the test program. The test procedure therefore differed somewhat between tests.

For tests on snow, the following general procedure was adopted:

1. Compact the snow with 50 vehicle passes over the test area.
2. Measure skid resistance, photograph the surface, and collect a snow sample for analysis.
3. Apply salt at the selected rate.
4. Traffic the test area for 50 vehicle passes.
5. Measure skid resistance, photograph the surface, and collect snow/snow-melt samples for analysis.
6. Repeat steps 4 and 5 to termination of test.

Step 1 was omitted in ice tests.

The trafficking was done by driving the test vehicle repeatedly, and as closely as possible, over the same wheel tracks. Vehicle passes were thus distributed randomly across the width of the test area in much the same way as a normal highway would be trafficked. Each vehicle pass was made in the opposite direction to that made in the previous pass. This procedure differs from normal operation where traffic flows in one direction only. In one-way flow, snow or melted snow is transported in the direction of flow, whereas in two-way flow with an equal number of passes in each direction there is no net transport of the melt. However, if the salt application is uniform over a sufficiently long section and the transport mechanism and rate are the same for flow in both directions, the salt concentration will remain constant along the length of the section whether the flow is one-way or equal pass two-way. On short sections, one-way flow will tend to transport melted snow out of the test section whereas two-way flow will tend to keep it in the test section. Two-way trafficking was used mainly for convenience, but the effect of this method of trafficking was probably not significantly different from that of normal highway trafficking and, on short sections, may even be closer to normal trafficking than one-way flow.

Snow samples were taken from the top surface layer of the test section immediately after a skid resistance measurement had been made in the track of the sliding test tire.

Ambient temperature, relative humidity, and solar radiation were taken from records compiled at the Pennsylvania State University Weather Station located at the University Park Campus. Solar radiation is given in gram calories per square centimeter of horizontal area accumulated over the hour preceding the time of recording.

Snow temperature was measured with a mercury thermometer placed in the snow adjacent to the test area. Pavement temperature was measured with a resistive surface probe placed in contact with the pavement adjacent to the test area and covered with snow.

Variations made in the test procedure are noted in the individual test descriptions.

A summary of the test results is given in Table B2. A more complete description of each test, graphs of the brake force measurements, and photographs of the test surfaces are available in CRREL Internal Report 774.

## Table B2. Summary of test results.

| Date | Test location | Time | Temperature (°F) Air | Snow | Pavement | Relative humidity (%) | Solar radiation (cal/cm²) | Pavement condition Start | End | Application rate (lb/LM) | No. of passes | Coeff. of friction μ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 Feb | Site 1 | 1300 | 25 | | | 60 | | 1 in. snow | ½ in. loose | 500 | 5 | 0.15 | |
| | PCC | 1330 | 26 | | | 57 | | over | crystal over | | 50 | 0.23 | |
| | | 1400 | 26 | | | 57 | | 1 in. ice | ½ in. hard ice | | 100 | 0.23 | |
| | | 1430 | 27 | | | 57 | | | | | 150 | 0.21 | |
| | | 1500 | 28 | | | 55 | | | | | 200 | 0.20 | |
| | | 1530 | 28 | | | 55 | | | | | 250 | 0.23 | |
| 15 Feb | Site 1 | 1200 | 25 | | | 65 | | 4 in. snow | Breaking up | 100 | 0 | 0.15 | Trafficking |
| | Bit. conc. | | | | | | | | | | 1 | 0.20 | done by |
| | | 1300 | 28 | | | 67 | | | | | 5 | 0.35 | 7-axle |
| | | 1400 | 29 | | | 68 | | | | | 10 | 0 50 | tractor- |
| | | | | | | | | | | | | | trailer |
| | Site 2 | 1200 | 25 | | | 65 | | 4 in. snow | Bare | 500 | 1 | 0.17 | and skid. |
| | Bit. conc. | | | | | | | | | | 2 | 0.18 | |
| | | 1300 | 28 | | | 67 | | | | | 10 | 0.18 | |
| | | 1400 | 29 | | | 68 | | | | | 15 | 0.17 | |
| | | | | | | | | | | | 20 | 0.25 | |
| 19 Feb | Site 7 | 1530 | 24 | 31 | 32 | 52 | - | ½ in. snow | Lateral | 100 | 0 | 0.18 | Condition |
| | PCC | 1600 | 24 | 30 | 32 | 50 | 34.8 | | grooves | | 50 | 0.19 | appeared |
| | | 1650 | 23 | 30 | 32 | 50 | - | | became | | 100 | 0.19 | to reach |
| | | 1700 | 23 | 29 | 31 | 48 | 17.4 | | visible | | 150 | 0.18 | steady |
| | | 1800 | 20 | 29 | 31 | 51 | 3.6 | | | | 200 | 0.16 | state. |
| | | 1830 | 18 | 28 | 31 | 54 | - | | | | 250 | 0.20 | |
| 5 Mar | Site 5 | 1200 | 17 | 19 | 29 | 67 | - | 1.1 in. snow | Clear | 125 | 0 | 0.12 | Weather + |
| | Sec 1 | 1300 | 19 | 21 | 29 | 62 | 58.2 | | | | 50 | 0.20 | pavement |
| | PCC | 1330 | 20 | 21 | 29 | 62 | - | | | | 100 | 0.18 | conditions |
| | | 1400 | 22 | 21 | 29 | 59 | 63.0 | | | | 150 | 0.18 | at Site 1- |
| | | 1430 | 20 | 22 | 29 | 59 | - | | | | 200 | 0.14 | 4 are the same. |
| | | 1500 | 21 | 23 | 30 | 56 | 55.8 | | | | 250 | 0.16 | All sites |
| | | 1530 | 22 | 23 | 30 | 55 | - | | | | 300 | 0.11 | clear |
| | | 1600 | 21 | 23 | 30 | 56 | 47.4 | | | | 350 | 0.15 | after 300 |
| | | 1630 | 21 | 23 | 30 | 56 | - | | | | 400 | 0.15 | passes. |
| | Site 5 | 1200 | 17 | 19 | 29 | 67 | - | 1.1 in. snow | Clear | 250 | 0 | 0.15 | |
| | Sec 2 | 1300 | 19 | 21 | 29 | 62 | 58.2 | | | | 50 | 0.22 | |
| | PCC | 1330 | 20 | 21 | 29 | 62 | - | | | | 100 | 0.19 | |
| | | 1400 | 22 | 21 | 29 | 59 | 63.0 | | | | 150 | 0.15 | |
| | | 1430 | 20 | 22 | 29 | 59 | - | | | | 200 | 0.15 | |
| | | 1500 | 21 | 23 | 30 | 56 | 55.8 | | | | 250 | 0.40 | |
| | | 1530 | 22 | 23 | 30 | 55 | - | | | | 300 | 0.58 | |
| | Site 7 | 1200 | 17 | 19 | 29 | 67 | - | 1.1 in. snow | Clear | 375 | 0 | 0.15 | |
| | Sec 3 | 1300 | 19 | 21 | 29 | 62 | 58.2 | | | | 50 | 0.30 | |
| | PCC | 1330 | 20 | 21 | 29 | 62 | - | | | | 100 | 0.60 | |
| | | 1400 | 22 | 21 | 29 | 59 | 63.0 | | | | 150 | 0.55 | |
| | | 1430 | 20 | 22 | 29 | 59 | - | | | | 200 | 0.60 | |
| | | 1500 | 21 | 23 | 30 | 56 | 55.8 | | | | 250 | 0.93 | |
| | Site 7 | 1200 | 17 | 19 | 29 | 67 | - | 1.1 in. snow | Clear | 500 | 0 | 0.15 | |
| | Sec 4 | 1300 | 19 | 21 | 29 | 62 | 58.2 | | | | 50 | 0.20 | |
| | PCC | 1330 | 20 | 21 | 29 | 62 | - | | | | 100 | 0.80 | |
| 7 Mar | Site 1 | 1000 | 23 | 16 | 32 | 68 | - | 1½ in. snow | Clear | 125 | 0 | 0.18 | Clear after |
| | PCC | 1030 | 24 | 19 | 32 | 62 | - | | after 300 | | 50 | 0.18 | 300 passes. |
| | | 1100 | 25 | 20 | 31 | 60 | 52.2 | | | | 100 | 0.18 | |
| | | 1130 | 27 | 20 | 31 | 57 | - | | | | 150 | 0.15 | |
| | | 1200 | 29 | 20 | 31 | 55 | 58.8 | | | | 200 | 0.16 | |
| | | 1230 | 30 | 21 | 31 | 51 | - | | | | 250 | 0.55 | |
| | | 1300 | 30 | 23 | 32 | 48 | 59.4 | | | | 300 | - | |

## Table B2 (cont'd). Summary of test results.

| Date | Test location | Time | Temperature (°F) Air | Snow | Pavement | Relative humidity (%) | Solar radiation (cal/cm²) | Pavement condition Start | End | Application rate (lb/LM) | No. of passes | Coeff. of friction μ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 Mar | Site 2 | 1000 | 23 | 16 | 32 | 68 | - | 1½ in. snow | Clea | 250 | 0 | 0.18 | Clear after |
| | PCC | 1030 | 24 | 19 | 32 | 62 | - | | after 300 | | 50 | 0.15 | 300 passes. |
| | | 1100 | 25 | 20 | 31 | 60 | 52.2 | | | | 100 | 0.13 | |
| | | 1130 | 27 | 20 | 31 | 57 | - | | | | 150 | 0.13 | |
| | | 1200 | 29 | 20 | 31 | 55 | 58.8 | | | | 200 | 0.10 | |
| | | 1230 | 30 | 21 | 31 | 51 | - | | | | 250 | 0.40 | |
| | | 1300 | 30 | 23 | 32 | 48 | 59.4 | | | | 300 | - | |
| | Site 3 | 1000 | 23 | 16 | 32 | 68 | - | 1½ in. snow | Clear | 375 | 0 | 0.18 | Clear after |
| | PCC | 1030 | 24 | 19 | 32 | 62 | - | | after 300 | | 50 | 0.12 | 300 passes. |
| | | 1100 | 25 | 20 | 31 | 60 | 52.2 | | | | 100 | 0.15 | |
| | | 1130 | 27 | 20 | 31 | 57 | - | | | | 150 | 0.15 | |
| | | 1200 | 29 | 20 | 31 | 55 | 58.8 | | | | 200 | 0.15 | |
| | | 1230 | 30 | 21 | 31 | 51 | - | | | | 250 | 0.25 | |
| | | 1300 | 30 | 23 | 32 | 48 | 59.4 | | | | 300 | - | |
| | Site 4 | 1000 | 23 | 16 | 32 | 68 | - | 1½ in. snow | Clear | 500 | 0 | 0.18 | Clear after |
| | PCC | 1030 | 24 | 19 | 32 | 62 | - | | after 300 | | 50 | 0.22 | 300 passes. |
| | | 1100 | 25 | 20 | 31 | 60 | 52.2 | | | | 100 | 0.15 | |
| | | 1130 | 27 | 20 | 31 | 57 | - | | | | 150 | 0.30 | |
| | | 1200 | 29 | 20 | 31 | 55 | 58.8 | | | | 200 | 0.95 | |
| 8 Mar | Site 5 | 0930 | 21 | 23 | 27 | 62 | - | 1-1½ in. ice | ½-1 in. ice | 500 | 0 | - | |
| | PCC | 1000 | 22 | 23 | 27 | 59 | 18.0 | covered | | | 1 | 0.18 | |
| | | 1030 | 22 | 23 | 27 | 59 | - | with ½-1 | | | 50 | 0.23 | |
| | | 1100 | 22 | 23 | 27 | 59 | 15.6 | in. snow | | | 100 | 0.21 | |
| | | 1130 | 22 | 23 | 28 | 59 | - | | | +500 | 400 | 0.23 | |
| | | 1200 | 23 | 24 | 28 | 57 | 12.0 | | | | 450 | 0.18 | |
| | | 1230 | 23 | 24 | 28 | 57 | - | | | | 500 | 0.22 | |
| | | 1300 | 23 | 25 | 28 | 57 | 20.4 | | | +1000 at | 550 | 0.22 | |
| | | 1330 | 23 | 25 | 28 | 57 | - | | | 600 passes | 650 | 0.22 | |
| | | 1400 | 22 | 24 | 28 | 59 | 14.4 | | | | 700 | 0.23 | |
| | | 1430 | 22 | 24 | 28 | 59 | - | | | | 750 | 0.20 | |
| | | 1500 | 21 | 23 | 28 | 62 | 11.4 | | | | 800 | 0.22 | |
| | | 1530 | 21 | 23 | 28 | 64 | - | | | | 900 | 0.24 | |
| | | 1600 | 21 | 23 | 28 | 64 | - | | | | 1000 | 0.20 | |
| | | | | | | | | | | | 1100 | 0.15 | |
| | | | | | | | | | | | 1200 | 0.15 | |
| | | | | | | | | | | | 1300 | 0.23 | |
| 9 Mar | Site 5 | 0900 | 25 | - | 31 | 74 | 9.6 | ¼ in. ice | Clear | 250 | 0 | 0.07 | Clear after |
| | Sec 1 | 0930 | 26 | - | 31 | 71 | - | | | | 50 | 0.18 | 150 passes. |
| | PCC | 1000 | 27 | - | 31 | 71 | 1[illegible] | | | | 100 | 0.22 | |
| | | 1030 | 29 | - | 31 | 69 | - | | | | 150 | - | |
| | Site 5 | 0900 | 25 | - | 31 | 74 | 9.6 | ¼ in. ice | Clear | 500 | 0 | 0.07 | Clear after |
| | Sec 2 | 0930 | 26 | - | 31 | 71 | - | | | | 50 | 0.18 | 100 passes |
| | PCC | 1000 | 27 | - | 31 | 71 | 18.0 | | | | 100 | 0.60 | |
| | By-pass | 1300 | 33 | - | - | 69 | 52.2 | ½-1 in. ice | Clear | 1000 | 0 | 0.23 | Clear after |
| | Sec 1 | 1330 | 34 | 32 | 32 | 65 | - | | | | 50 | 0.40 | 100 passes. |
| | PCC | 1400 | 36 | 32 | 32 | 61 | 60.0 | | | | 100 | 0.65 | |
| | | 1430 | 36 | 32 | 32 | 61 | - | | | | | | |
| | | 1500 | 36 | 32 | 32 | 61 | 39.6 | | | | | | |
| | | 1530 | 36 | 32 | 32 | 61 | - | | | | | | |
| | | 1600 | 36 | 32 | 32 | 64 | 30.0 | | | | | | |
| | By-pass | 1300 | 33 | - | - | 69 | 52.2 | 1 in. ice and | Snow and | 250 | 0 | 0.16 | Appeared to |
| | Sec 2 | 1330 | 34 | 32 | 32 | 65 | - | ½ in. packed | ice redis- | | 50 | 0.18 | reach |
| | PCC | 1400 | 36 | 32 | 32 | 61 | 60.0 | snow | tributed | | 100 | 0.16 | steady- |
| | | 1430 | 36 | 32 | 32 | 61 | - | | | +500 | 150 | 0.16 | state pave- |
| | | 1500 | 36 | 32 | 32 | 61 | 39.6 | | | | 200 | 0.16 | ment condi- |
| | | 1530 | 36 | 32 | 32 | 61 | - | | | | 250 | 0.18 | tions. |
| 16 Mar | Sections | 1200 | 34 | 32 | - | 92 | 50.2 | 2 in. snow | Clear | 0 | 0 | - | After 40 |
| | 1,2,3,4 | 1230 | 34 | 32 | 32 | 92 | - | | | | 40 | 0.5 | passes Site 2 |
| | PCC | | | | | | | | | | | | coef of fric- |
| | | | | | | | | | | | | | tion was 0.4. |

## APPENDIX C. ROCHESTER INSTITUTE OF TECHNOLOGY FIELD STUDY

A.C.H. Hu, T.C.T. Lam, and R.H. Sammons

### INTRODUCTION

Since the CRREL surface friction gauge was not available until the final one of the six field tests that were conducted at RIT, the stopping distance of a passenger car was used to relate the effectiveness of a deicing chemical acting on a snow-covered pavement. We report here the data that were used to determine the relationship between the chloride concentrations and the stopping distances at various driving speeds under artificial trafficking conditions at air temperatures ranging from 21° to 32°F.

Two test sites on the RIT campus were used: Site 1, consisting of approximately 0.2 mile of Ward Road, and Site 2, Parking Lot B.

### SALT APPLICATION PRACTICE AT RIT

The RIT Campus Services Department uses a dump truck with a front-mounted snow plow and chassis-mounted salt hopper for winter maintenance. The hopper has an effective capacity of 4 tons and a manually controlled gate. The salt is fed by a conveyor belt driven with an independent engine. The application rate may be controlled by a throttle. A spinner spreads the salt, and its distribution may be somewhat adjusted by a clutch. The normal practice is to spread the salt at full throttle, with one pass on 22 ft of road width (2-lane). A field test at RIT demonstrated that the actual spread pattern covered a width of 26 ft. Campus Services indicated that an average of 4 tons of rock salt is spread on the 13 miles of camous roads for each application. This rate is equivalent to 284 lb/LM, assuming the 26-ft distribution pattern, or 300 lb per 11 ft of lane mile if the nominal distribution width of 22 ft is used. A measurement of salt flow with full throttle in a one-minute time interval was 185.5 lb. This is equivalent to 257 lb/LM when the salt truck is driving at the usual operating speed of 20 miles per hour. A salt application rate of 500 lb/LM is roughly equivalent to 5000 mg/L of chloride concentration as shown in a field test.

The rock salt was supplied by International Salt Company, Retsof, New York, and stored in a heated garage. Our laboratory analysis showed a stockpile moisture content of 1.5%, determined by ASTM D1557-67T. Two sieve analyses were performed, one on an oven-dried sample, the other at stockpile moisture content (Fig. C1). AASHTO T27-60 was followed; however, the shaking time used was 1 minute in order to minimize breakage of salt grains. The gradations for both oven-dried and stockpile samples were rather uniform. The percentage of grains size smaller than 1.0 mm was relatively low (less than 5% for the stockpile sample and less than 13% for the oven-dried sample).

The chloride content of the salt was found to be 58.82%, as compared with a reagent grade sodium chloride of 60.65% chloride. The difference can be attributed to impurities and additives.

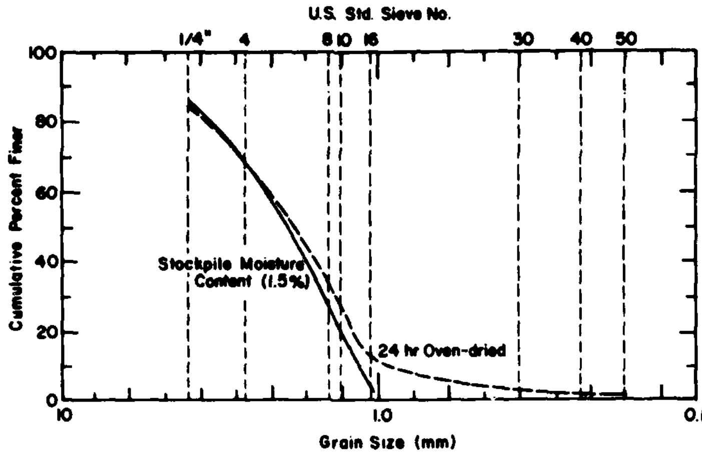


*Figure C1. Gradation of salt used in RIT tests.*

## FIELD STUDY

Stopping distances at various driving speeds and chloride concentrations were studied in five tests during the period of 23 January to 1 March 1978 on Ward Road (Test Site 1). Approximately 0.2 mile of this road was selected because of its flatness. The road consists of two 11-ft lanes of dense-graded asphaltic concrete pavement with a ¼-in./ft crown slope. Ward Road was open to traffic, plowed and salted on a routine basis until 22 January. After that the 0.2-mile section of Ward Road was blocked and remained closed. The last salt application was on 22 January. The total amount of salt applied on the campus for the winter season from 27 November 1977 to 22 January 1978 was 100 tons as estimated by Campus Services. The total salt applied is equivalent to 7100 lb/LM.

The snow samples taken on 22 January showed an average chloride concentration of 4728 mg/L with the highest concentration being 12,220 mg/L. It indicated a significant residual effect. No more salt was applied for the five field tests performed in this period at test site 1.

After 1 March, there was no significant snowfall and the snow accumulation on Ward Road had melted. The sixth test, which was the last field test, was carried out on 8 March in Parking Lot B (Test Site 2). There was about 1 in. of densely packed snow This testing site is also a dense-graded asphaltic concrete pavement. The CRREL surface friction gauge was used during this test.

## FIELD TESTS

### Stopping distance

In order to minimize the factors involved in stopping distance measurement, only one automobile and one driver were used in the test. The car was an 8-cylinder Dodge Dart weighing 2941 lb. Tires were Firestone Radial 500, size ER 78-14; front tires had a summer tread and those in the rear had a studded snow tread. The driving speeds were 20, 25, 30, 35 and 40 mph. The test car was used for trafficking the snow. The number of passes was recorded, and panic brake stops made (i.e. locked wheel mode) were made after an arbitrary number of passes. The car was allowed to stop without steering correction. The distance was then measured from the point of initial braking, marked by a road cone, to the point of stopping.

### Snow sampling

Snow samples were collected at various points across the road profile after the artificial trafficking. The locations of sampling points and the distribution of chloride concentration are sketched and shown in Figure C2–C8. The samples were collected by scraping the snow completely from the pavement. Approximately 250 mL of snow was taken for each sample. The packed snow thickness during the testing period ranged from 1/2 to 2 in.

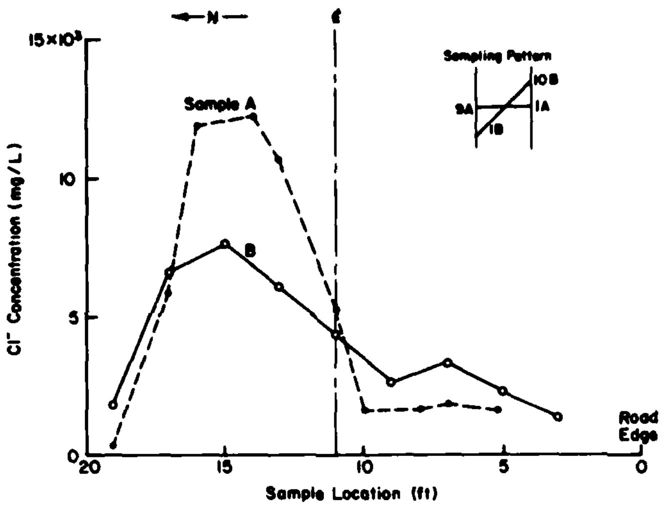


*Figure C2. Chloride distribution, test 1, test site 1, 23 January, 1978. Initial snow depth 1 in.*

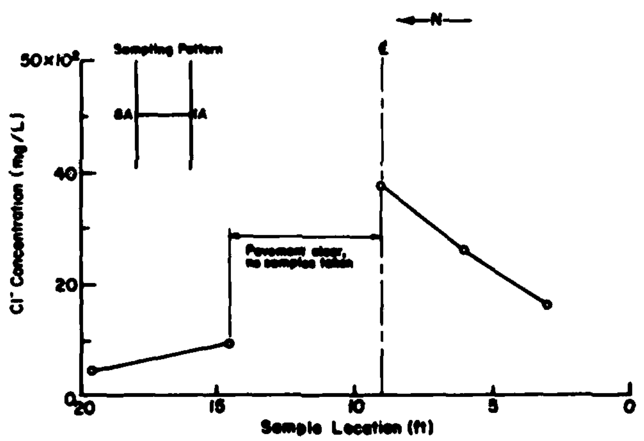


*Figure C3. Chloride distribution, test 2, test site 1, 2 February, 1978. Initial snow depth—trace.*

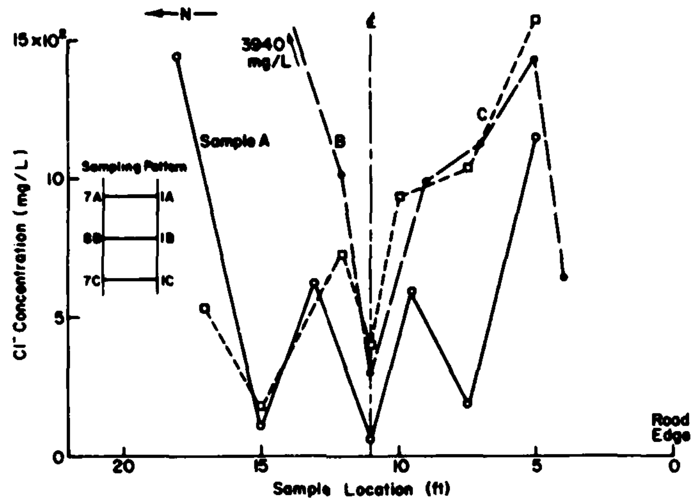


*Figure C4. Chloride distribution, test 3, test site 1, 23 February, 1978. Initial snow depth 1-2 in.*

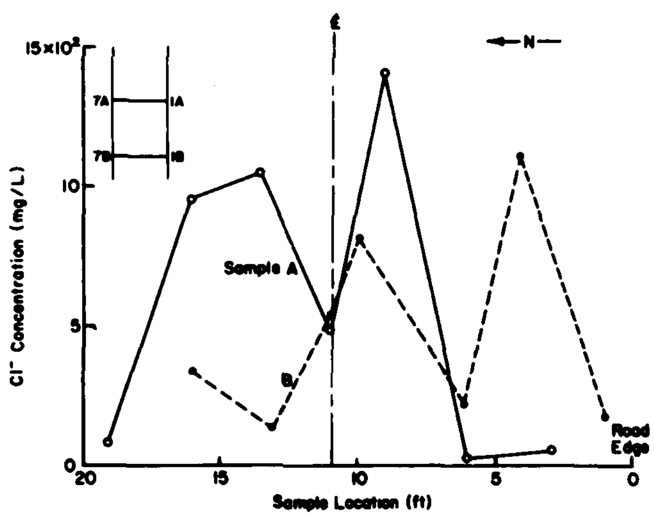


*Figure C5. Chloride distribution, test 4, test site 1, 6 February 1978. Initial snow depth 1-2 in.*

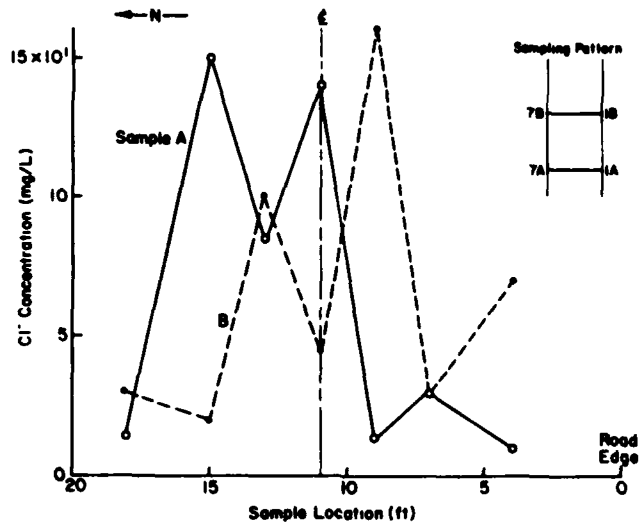


*Figure C6. Chloride distribution, test 5, test site 1, 27 February 1978. Initial snow depth 1-2 in.*

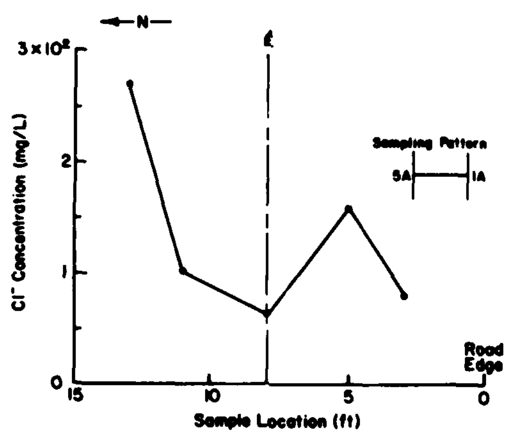


*Figure C7. Chloride distribution before salt application, test 6, test site 2, 8 March 1978. Initial snow depth 1 in. (compacted).*

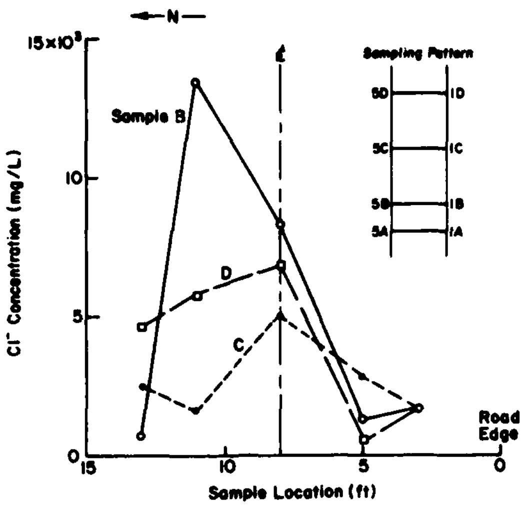


*Figure C8. Chloride distribution after salt application, test 6, test site 2, 8 March 1978.*

## LABORATORY DETERMINATION OF CHLORIDE CONCENTRATION

The mercuric nitrate method was used in the determination of chloride concentration, following the procedure described in APHA (1975). Sample sizes ranging from 2.0 to 25.0 mL were used, depending on the concentration of chloride. A sample calculation is shown below:

$$\text{mg/L Cl}^- = \frac{(A-B) \times N \times 35.45 \times 1000}{\text{mL sample size}}$$

where $A$ = mL of titrant used for sample

$B$ = mL of titrant used for distilled water blank

$N$ = normality of mercuric nitrate titrant

**Example, sample 6A, field test 1, 23 January 1978**

Sample size = 2.0 mL

$A = 24.2$

$B = 0.05$

$N = 0.0141$

$$\text{Cl}^- = \frac{(24.2 - 0.05) \times 0.0141 \times 35.45 \times 1000}{2} = 6036 \text{ mg/L}.$$

Due to the high chloride concentration in all samples, the blank readings were taken as zero for tests 2–6.

## TEST RESULTS

### Development of model

The field study results at test site 1 are summarized in Table C1. Insufficient data were collected for driving speeds of 35 and 40 mph. The stopping distances for driving speeds of 20, 25 and 30 mi/hr are plotted against the chloride concentrations, as shown in Figures C9, C10 and C11, respectively. The data revealed that they might fit an assumed mathematical model:

$$S = \frac{V^2}{30}\left(\frac{1}{C_1 \log Cl^- + C_2}\right)$$

where $S$ = stopping distance (ft)

$V$ = driving speed (mph)

$C_1$ = friction coefficient associated with chloride concentration

$C_2$ = friction coefficient for snow- or ice-covered pavement, usually assumed to be in the range of 0.05 to 0.10

$Cl^-$ = average chloride concentration (mg/L per lane).

**Table C1. Summary of field test results at test site 1—Ward Road.**

| *Driving speed (mph)* | *Average stopping distance (ft)* | *Average $Cl^-$ concentration per 11-ft lane, (mg/L)* | *Lane* |
|---|---|---|---|
| 20 | 27.0 | 5523 | E |
| 20 | 30.0 | 979 | E |
| 20 | 29.0 | 454 | W |
| 20 | 38.0 | 73 | E |
| 20 | 49.0 | 49 | W |
| 25 | 42.0 | 2776 | W |
| 25 | 39.0 | 5523 | E |
| 25 | 33.0 | 2656 | E |
| 25 | 25.7 | 705 | W |
| 25 | 44.5 | 890 | E |
| 25 | 48.5 | 1792 | W |
| 25 | 62.0 | 467 | W |
| 25 | 64.5 | 580 | E |
| 25 | 52.0 | 49 | E |
| 25 | 62.0 | 96 | W |
| 30 | 54.0 | 2776 | W |
| 30 | 54.0 | 5523 | E |
| 30 | 53.3 | 2656 | E |
| 30 | 46.0 | 705 | W |
| 30 | 66.5 | 489 | E |
| 30 | 66.5 | 550 | W |
| 30 | 68.0 | 491 | E |
| 30 | 61.5 | 644 | W |
| 30 | 64.5 | 49 | E |
| 30 | 69.0 | 96 | W |
| 35 | 76.5 | 2776 | W |
| 35 | 83.0 | 73 | E |
| 35 | 87.5 | 49 | W |
| 40 | 88.0 | 5523 | E |
| 40 | 62.0 | 2656 | W |
| 40 | 65.0 | 705 | W |

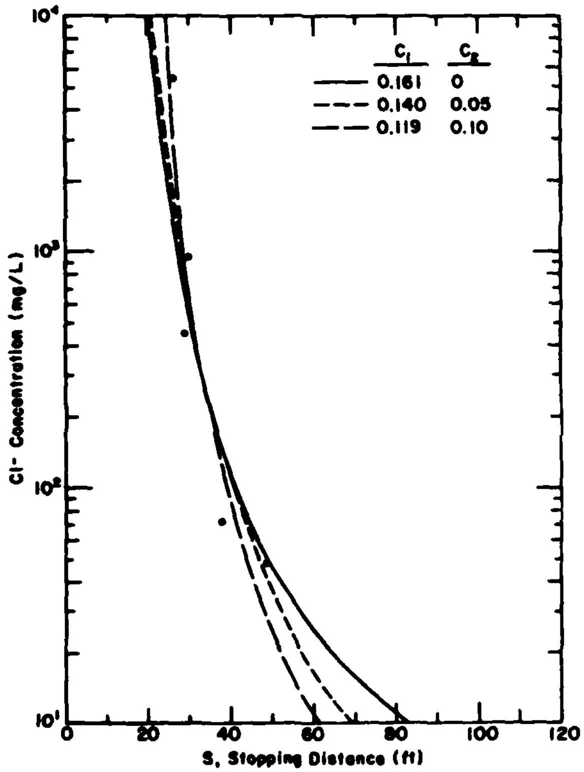


*Figure C9. Chloride concentration vs stopping distance, vehicle speed V = 20 mph.*

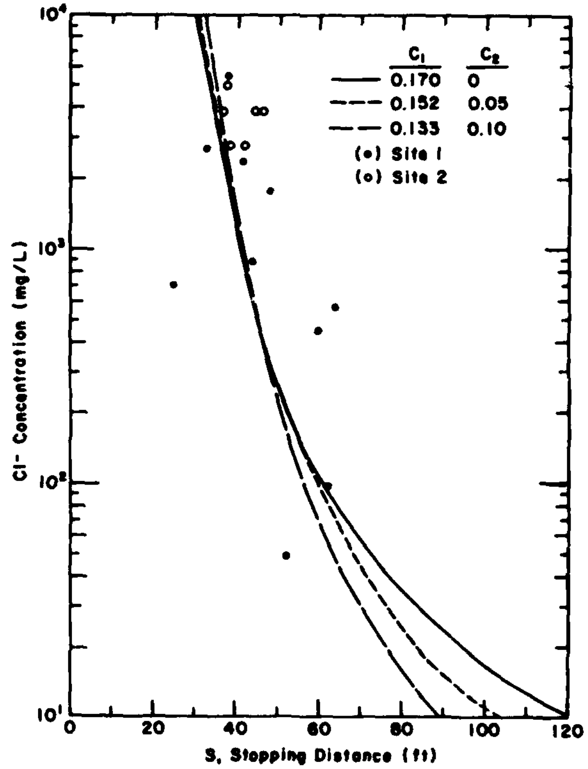


*Figure C10. Chloride concentration vs stopping distance, vehicle speed V = 25 mph.*

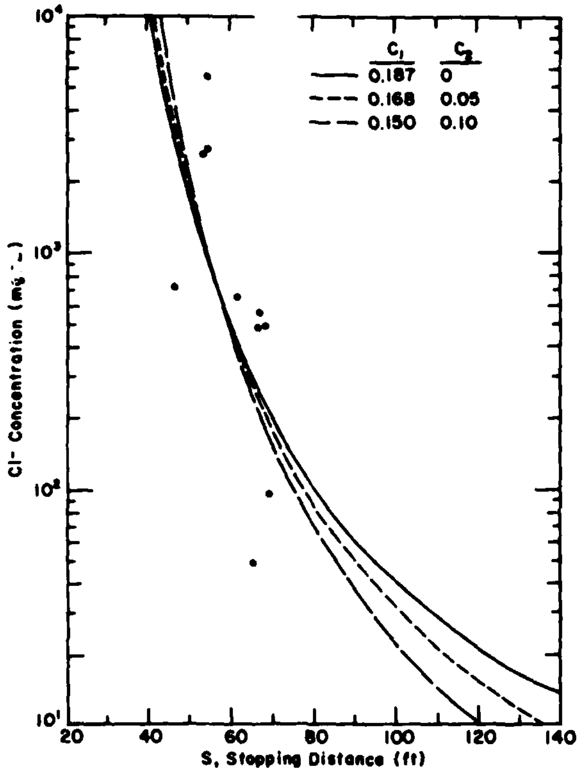


*Figure C11. Chloride concentration vs stopping distance, vehicle speed V = 30 mph.*

The method used in developing the parameter $C_1$ and the model was as follows. For a given driving speed, stopping distances are field measured. Next, knowing the chloride concentration and selecting a value of $C_2$, the value of $C_1$ can be generated from the equation.

The $C_2$ values used are assumed to be 0, 0.05, and 0.10 respectively. When $C_2 = 0$, $C_1$ represents the overall friction coefficient. When $C_2 = 0.05$ to $0.10$, $C_1$ represents the friction coefficient associated with chloride concentration. Once the model is established, a series of chloride concentrations at a given speed is assumed, and the corresponding stopping distances are calculated. Graphs of the results are given in Figures C9-C11, for driving speeds of 20, 25, and 30 mi/hr, respectively. The computer program used is given in Figure C12.

The following example illustrates the development of the model. Driving speed $V = 20$ mph.

$$S = \frac{V^2}{30}\left(\frac{1}{C_1 \log \mathrm{Cl}^- + C_2}\right) = \frac{400}{30}\left(\frac{1}{C_1 \log \mathrm{Cl}^- + C_2}\right) .$$

Assuming $C_2 = 0$, and with the known field data of $S$ and $\mathrm{Cl}^-$ as listed in Table C1, then average $C_1$ is calculated to be 0.161, and

$$S = \frac{400}{30}\left(\frac{1}{0.161 \log \mathrm{Cl}^-}\right) .$$

```
 11:14 MAR 14,'78 ID=362C
JOB 67395,UA,H070SMAM511A(UCC),7 . TONY LAM
LIMIT (TIME,1),(CORE,8),(LO,50)
     ROSS* PUT AFTER LIMIT CARD IN YOUR DECK  *ROSS        57
FLAG OB ,PL=50
   * FLAG VERSION 000
   * AVAILABLE MEMORY:
   *     PROGRAM & INITIALIZED VARIABLES = 1539 (WORDS)
   *     NON-INITIALIZED VARIABLES = 3580 (WORDS)
   *     TOTAL = 5119 (WORDS)

          C THIS PROGRAM IS FOR FINDING THE RELATION BETWEEN CL & S,
          C  CL  CHLORIDE APPLIED ON THE ROAD SURFACE
          C  S,SD & SDD STOPING DISTANCE
          C  C2 & C1  COEFICIENCE OF FRICTION
          C  V & VV VELOSITY
          C
                       DIMENSION S(100),CL(100)
           100         READ(105,1)N,VV,C2
           1           FORMAT(I10,2F10.5)
                       IF (N .EQ. 0) GO TO 999
                       READ(105,2)((S(I),CL(I)),I=1,N)
           2           FORMAT(2F10.5)
                       V=VV*5280.0/3600.0
          C  ANALIZE DATA,CALCULATE THE COEFFICIENCE
                       TC=0.0
                       DO 10 L=1,N
                       C=(V**2/(2.0*32.174*S(L))-C2)/ALOG10(CL(L))
           10          TC=TC+C
                       C1=TC/FLOAT(N)
                       WRITE(108,3)VV,C1,C2
           3           FORMAT('1  V=',F6.2,'MPH    C1=',F10.8,'    C2=',F10.8/)
          C  PRINT THE INPUT DATA.
                       WRITE(108,8)
           8           FORMAT(/14X,'FIELD DATA',//10X,'CL',15X,'SD'/)
                       DO 90 I=1,N
                       WRITE(108,9) CL(I),S(I)
           9           FORMAT(2F15.2)
           90          CONTINUE
          C  PRINT A TABLE FOR SD & CL ,ACCORDING TO ANALYTICAL C1.
                       WRITE(108,7)
           7           FORMAT('  TABLE IS DEPENED ON CALCULATED VALUES OF C1 & C2'/)
                       WRITE(108,4)
           4           FORMAT(//,5X,'CL',8X,'S',/)
                       DO 20 M=1,109
                       IF( M-10 ) 30,30,40
           30          CLT=10.0*FLOAT(M)
                       GO TO 50
           40          CLT=100.0*FLOAT(M-9)
           50          SD=V**2/(2.0*32.174*(C1*ALOG10(CLT)+C2))
                       WRITE(108,5)CLT,SD
           5           FORMAT(1X,F8.2,1X,F8.3)
           20          CONTINUE
                       GO TO 100
           999         STOP
                       END


   * ACTUAL PROGRAM SIZE:
   *     PROGRAM & INITIALIZED VARIABLES = 237 (WORDS)
   *     NON-INITIALIZED VARIABLES = 213 (WORDS)
   *     TOTAL = 450 (WORDS)


COMPILE TIME = 0000.76
```

*Figure C12. Program for computing relation between chloride concentration and stopping distance.*

Similarly, for $C_2$ values of 0.05 and 0.1, the model would be

$$S = \frac{400}{30}\left(\frac{1}{0.149 \log Cl^- + 0.05}\right) \text{ and } S = \frac{400}{30}\left(\frac{1}{0.119 \log Cl^- + 0.10}\right) .$$

The model is summarized in Table C2.

**Table C2. Friction coefficient at various driving speeds.**

| *V = 20 mph* | *V = 25 mph* | *V = 30 mph* | *C* |
|---|---|---|---|
| 0.161 | 0.170 | 0.187 | 0 |
| 0.140 | 0.152 | 0.168 | 0.05 |
| 0.119 | 0.133 | 0.150 | 0.10 |

As observed from the three graphs, the data fit fairly well with the computer-calculated curves. With a driving speed of 20 mph, the stopping distance is slightly affected by the chloride concentration when it is above 100 mg/L. For a driving speed of 25 mph, an increase of chloride concentration beyond 1000 mg/L reduces the stopping distance only about 10 ft, as compared to a 20-ft decrease when the chloride concentration is increased from 100 to 1000 mg/L. A similar situation is observed for a driving speed of 30 mph. As for driving speeds of 35 and 40 mph, it is believed that the general trend is similar to those of 20, 25, and 30 mph, except that the stopping distance would be greatly increased.

**Model testing (test 6)**

The availability of the CRREL surface friction gauge after all snow had melted on Ward Road (test site 1) led to the selection of RIT Campus Parking Lot B because it has the same type of pavement as test site 1 and a dense-packed layer of snow remained there. Salt was applied at the 257 lb/LM rate used by RIT Campus Services, using the spinner distribution. Samples of the salt were collected on plastic sheets during application and the amount weighed; one sample corresponded to an application rate of 248 lb/LM, the other a rate of 1140 lb/LM. The latter sample was taken from a location to the right of the vehicle path, and the former to the left. The spinner was centrally positioned.

Trafficking began immediately after salt application, and after every 20 wheel passes a skid test was performed. The results are summarized in Table 3 and in Figure C13. Data collected in this test were also included in plotting Figure C9. These results showed that the stopping distance and chloride concentration correlated fairly well. The stopping distances were slightly longer than those predicted from the model, but this probably resulted because the snow was left on this testing site for quite a long time without plowing and it was densely packed with 1/2 in. or so of ice formation. Air temperature varied from 27° to 34°F (-2.7 to +1°C).

Figures C14–C16 show test site 2 during the test period when skid tests were performed and the coefficient of friction was measured using the CRREL surface friction gauge. As can be seen from Figure C13, there appears to be little correlation between the two measures of surface character, and though the coefficient of friction shows a slightly increasing trend, the skid distance shows an increase after 140 wheel passes (the last test run) after a pronounced reduction in skid distance. The combination of high incident solar radiation, snow and ice surface, and intermittent patches of clear pavement undoubtedly influenced these results.

Table C3. Summary of field test results at test site 2.

| Driving speed mi/hr | Average stopping distance, ft | Average Cl concentration per 11-ft lane, mg/L | Lane |
|---|---|---|---|
| 25 | 38.0 | 5094 | E |
| 25 | 38.0 | 5094 | E |
| 25 | 37.0 | 2744 | E |
| 25 | 42.0 | 2744 | E |
| 25 | 45.0 | 3924 | E |
| 25 | 36.0 | 3924 | E |
| 25 | 46.0 | - | - |

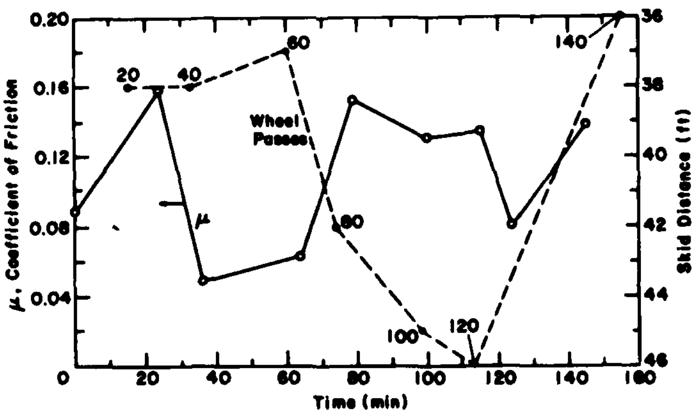


*Figure C13. Test 6, test site 2, 8 March 1978. Comparison of skid (stopping) distance of test sedan (dashed line, with cumulative number of wheel passes indicated) and coefficient of friction measured with CRREL surface friction gauge.*

*Figure C14. Skid distance was measured after every 20 wheel passes of sedan.*

*Figure C15. CRREL surface friction gauge in use at test site 2 (8 March 1978) to measure coefficient of friction in wheel track of test sedan.*

*Figure C16. Samples of snow were removed on both sides of wheel tracks for analysis of chloride ion concentration.*

## CONCLUSIONS

On the basis of the findings from this investigation, the following conclusions are drawn:

1. It has been demonstrated conclusively that there is a relationship between the chloride concentration and automobile stopping distance on snow-covered pavement.
2. No significant reduction of stopping distance is obtained when the chloride concentration is higher than 1000 mg/L per lane for a driving speed of 30 mi/hr or less.
3. There is no significant effect on the established relationship between the chloride concentration and stopping distance when the pavement temperature is between 21° and 32°F.
4. The overall friction coefficients, found in this study, are 0.161, 0.170, and 0.187 for driving speeds of 20, 25, and 30 mph, respectively. AASHTO's design criteria for wet pavements indicated a friction coefficient of 0.36 at a speed of 30 mph. In other words, the coefficient of friction on snow-covered pavement is about half of that for wet pavement.

## RECOMMENDATIONS

1. More data are needed to determine the reproducibility of the present mathematical model.
2. Snow tires without studs should be used in order to differentiate their effect.

3. The CRREL surface friction gauge should be used for correlation in the above studies.

4. If possible, pavement temperatures between 20° and 0°F should be studied separately in order to establish the temperature effect. The van't Hoff-Arrhenius model can be tried in simulation of the temperature effect.

5. The salt application rates, their distribution pattern as affected by wind, and the chloride concentration should be studied in as much detail as possible so that the optimum range of application rates can be narrowed.

6. Winter driving speed in residential areas on snow-covered pavement is recommended to be no more than 30 mph.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Minsk, L. David
Optimizing deicing chemical application rates / by L. David Minsk. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory, Hanover, N.H. Springfield, Va.: available from National Technical Information Service, 1982.
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Bibliography: p. 31.
1. Deicing materials. 2. Ice. 3. Rates. 4. Snow. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 82-18.

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8